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**GUIDELINES FOR GROUND MOTION DEFINITION
FOR THE EASTERN UNITED STATES**

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GUIDELINES FOR GROUND MOTION DEFINITION FOR THE EASTERN UNITED STATES*

R. C. Gwaltney G. A. Aramayo
R. T. Williams

ABSTRACT

Guidelines for the determination of earthquake ground motion definition for the eastern United States are established here. Both far-field and near-field guidelines are given. The guidelines were based on an extensive review of the current procedures for specifying ground motion in the United States. Both empirical and theoretical procedures were used in establishing the guidelines because of the low seismicity in the eastern United States. Only a few large- to great-sized earthquakes ($M_s > 7.5$) have occurred in this region, no evidence of tectonic surface ruptures related to historic or Holocene earthquakes has been found, and no currently active plate boundaries of any kind are known in this region. Very little instrumented data have been gathered in the East. Theoretical procedures are proposed so that in regions of almost no data, a reasonable level of seismic ground motion activity can be assumed. The guidelines are to be used to develop the safe shutdown earthquake (SSE). A new procedure for establishing the operating basis earthquake (OBE) is proposed, in particular for the eastern United States. The OBE would be developed using a probabilistic assessment of the geological conditions and the recurrence of seismic events at a site. These guidelines should be useful in development of seismic design requirements for future reactors.

1. INTRODUCTION

The seismic design problem varies considerably in the United States because of the markedly different seismicity in the East and West. In the western United States, particularly in California and Nevada, the seismicity is relatively high. More large- and moderate-sized earthquakes have occurred in these two states than in any other part of the continental United States. Tectonic surface ruptures related to historic earthquakes (0 to 200 years before present) and Holocene earthquakes (0 to 10,000 years before present) are common. In addition, the active

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plate boundary represented by the 1000-km-long San Andreas fault system makes part of the western United States very different from other seismically active parts of the country. By contrast, the eastern United States has almost none of the characteristics exhibited in the western United States. Seismicity is low; large- to great-sized earthquakes occurred only in 1811, 1812, and 1886; and no evidence of tectonic surface ruptures related to historic or Holocene earthquakes has been found. Also, no currently active plate boundaries of any kind are known there.

Planning and engineering of structures in the eastern United States should be based on knowledge about the causes of seismicity in the East. Although epicenters in the East are broadly scattered, important historical seismicity is concentrated in only a few zones. Focal depths extend from near the surface to midcrustal depths of ~20 km, which indicates the depth range of seismogenic structure. A plausible explanation for some eastern seismicity is that the larger earthquakes are caused by reactivation of ancient fault systems that were formed as early as the Precambrian time. These fault systems could be zones of weakness that are subject to movement when stresses are of sufficient magnitude and are oriented in an appropriate direction.

The possibility of earthquake damage is one among many factors that affect planning and design decisions. Ultimately, the degree to which the earthquake threat influences decisions comes down to a judgment about its relative importance. Formation of this judgment depends on estimates of the likelihood of earthquake occurrence and the severity of earthquake effects. To a certain extent, such estimates can be derived from the historical record of seismicity, but this record is clearly inadequate in many areas because it is so short compared with the recurrence time of major earthquakes. This problem of incompleteness of the historical record is acute in the eastern United States, where the rate of occurrence of major earthquakes is very low relative to that in the West. A major earthquake occurs somewhere in the eastern United States only about every 50 to 100 years. One might think that the relatively low seismicity of the East makes the earthquake threat in that region insignificant compared with the other factors, and many people do take this view.

However, the low seismicity of the East compared with the West is offset by some very important differences between the regions:

- Lower attenuation of seismic waves in the East causes shaking to extend over much larger areas for earthquakes of comparable magnitude. Higher population density in the East means greater exposure to damage.
- Lower earthquake awareness in the East has led to lower standards of design for and preparedness for earthquakes.

There are no easy solutions or quick fixes in dealing with the earthquake threat to the eastern United States, and much study must still be done to understand the geologic origin of the eastern United States seismicity.

However, the design of critical structures must continue, and the possibility that an earthquake may strongly shake the structures must be taken into account. The guidelines for developing the safe shutdown earthquake (SSE) for the eastern United States are shown in Fig. 1. The guidelines for near-field ground motion will be discussed later since most seismic engineers would specify a site for a critical structure well away from the site of known seismic activity. The general procedure used for seismic design of nuclear power plants, including breeder reactors, is given in the *Code of Federal Regulations*, 10 CFR 100, Appendix A. The procedure exists for establishing an SSE, which is based on the maximum ground motion at the site, and an operating basis earthquake (OBE), which in general is based on at least one-half ground acceleration magnitude of the SSE. Both of these design earthquakes are to be represented by response spectra.

There is a fundamental factor that distinguishes seismic and indeed all natural and external hazards as possible accident initiators from accident initiators that arise from causes within the plant. The public is at risk from earthquakes whether or not the nuclear plant exists.¹ A more accurate assessment of the seismic risk would be to assume that the risk to the public when the nuclear power plant does not exist is the background seismic risk. The additional risk due to the nuclear plant would be called the incremental seismic risk. As an alternative or supplement to the present thinking on safety, the acceptable incremental

Fig. 1. Ground motion guidelines for a safe shutdown earthquake in eastern United States.

seismic risk could be specified in terms of some "small" percentage of the background seismic risk. This approach has a number of advantages:

- Engineers familiar with the seismic design of nuclear and conventional facilities can give many examples of how the design of nuclear power plants is much more conservative than the design of conventional facilities.
- A comparison of background and incremental seismic risk would provide the public, the Nuclear Regulatory Commission, and utilities with precisely the information needed for decisions on whether reducing the incremental seismic risk is very effective in reducing the total public seismic risk.
- The comparison between background and incremental seismic risk will be more credible than a comparison of nuclear seismic risk with a numerical goal.
- Both background and incremental seismic risks are involuntary.

Such a consideration of incremental seismic risk for nuclear power plants would still require design for the SSE. A proposed design procedure for the OBE will be given in the last section of these guidelines.

2. GROUND MOTION GUIDELINES FOR A SAFE SHUTDOWN EARTHQUAKE IN THE EASTERN UNITED STATES

According to the guidelines three different methods can be used to develop the ground motion definition for a site. The choice of the method to be used should be made by an oversight committee of senior engineers and earth scientists. The committee is needed because of the diversity of opinions by "experts" on almost any variable or parameter associated with seismicity.² A panel of geologists and seismologists should provide expertise to interpret available geological and seismological data.

The one method that is the most conservative is based on the use of the maximum assumed historical seismic event in the tectonic region of the site or in tectonic regions near the site. Appendix A contains a discussion of tectonic regions or plates and a description of the way they are delineated. The region in which the site is located will control the maximum ground acceleration for the facility design. Another procedure is to use a seismic source zone map that shows zones where the maximum ground motion is considered the same over each zone. One of the latest seismic source zone maps of the United States is presented in Appendix B. From these maps, the maximum magnitude for each zone can be found. Another place to look for maximum earthquake values are earthquake catalogs such as the *Earthquake History of the United States*.³ These sources give the ground motion definition in magnitude and Modified Mercalli Intensity (MMI) values. A description of these measures of earthquake size can be found in Appendixes C and D. Since most of the historical data in the East have been developed into MMI values and body wave (m_b) magnitudes, relationships between these values and ground motion parameters (acceleration, velocity, displacement — both horizontal and vertical) must be used to calculate the maximum ground motion parameters. In Appendix E, relations are listed that can be used to convert both m_b and MMI to both horizontal and vertical ground motion parameters as well as relations that can be used to convert m_b to MMI. One such relation for converting MMI to acceleration is Trifunac's, which allows the effect of soil or rock conditions at the site to be considered. However,

all the conversion relations in Appendix E were developed using western data with the exception of the South Carolina relation, which is based on data from that region.

The response spectra for the site can be developed by scaling a standard response spectra by the maximum ground acceleration, velocity, and displacement at the site. In Appendix F three "standard" response spectra shapes are discussed. From the discussion in the chapter, the Newmark and Hall spectra shape — which can be used for conservative and probabilistic studies — is recommended for use. With the Newmark and Hall Spectra Shape, both a median (50%) and a median plus one sigma (84.1%) response spectra can be developed.

The method described above establishes the ground motion parameters for the so-called "floating earthquake." This concept assumes that ground motion at the site occurs as if the structure were located on or over the epicenter of the largest assumed historical earthquake that has ever occurred in the tectonic region or seismic source zone. An alternative to the use of the largest historical event is the "site-specific" earthquake. The series of steps associated with this definition for the ground motion is given in the following discussion and is based on using a combination of historical data and theoretical considerations or expert opinion to develop the ground motion definition for site-specific spectra.

In the eastern United States, the low level of seismic activity and the lack of instrumented records make it difficult to develop design spectra using historical data alone. The capable faults that affect the site must be determined as well as any surface faulting. The capable fault can be based on known historical seismicity or geologic evidence of past activity.

For each capable fault, the largest credible earthquake (LCE) must be determined. If there has been historical seismic activity along the fault, the LCE must be at least as great as the largest historical earthquake recorded for the fault. In case the fault has the potential to cause an earthquake larger than any historically recorded, the magnitude of this earthquake for the potentially largest LCE must be determined. This determination may be based on the size of the fault or by other theoretical methods.⁴ The potential magnitude can be approximated by the

seismic moment ($M_0 = \mu \bar{D}WL$, where L is fault length, $\bar{D}$ is average dislocation, W is fault width, and μ is rigidity). Source parameters ($\bar{D}$, W , L) for eastern United States earthquakes are discussed in Appendix G. The relations between seismic moment and the other magnitude parameters for earthquakes such as m_b are given in this appendix. The relations between source parameters and seismic moment in Appendix G can be used to give an estimate of earthquake size or magnitude based on geological studies to measure the source parameters. For past historical worldwide earthquakes, relations between seismic moment, source parameters, and magnitudes or size are shown in Table 1.

Calculations of seismic moment can be made for any faults discovered or known in a region; they can even be made for very large old faults. Such a calculation could lead to an overly conservative estimate of the earthquake size. However, by using recurrence relations, probabilistic analysis, and expert opinion, a decision on the conservatism of the calculated earthquake size can be made. Appendixes H, I, and J give discussions of probability, recurrence, and seismic probabilistic analysis. An earthquake that is too large based on these probabilistic studies or has too low a probability of occurrence should be considered too conservative. Recurrence relations for regions in the eastern United States are given in Appendix I, and parameters that can be used in the standard recurrence relation for seismic source zones in the United States are given in Appendix B. The recurrence relations represent the expected rates of seismic energy release within the region or seismic source zone based on a statistical interpretation of the past seismic record. The result of probability calculations should normally be in terms of probability of occurrence of intensity or magnitude and/or peak ground acceleration. The calculational methods used to develop seismic probabilistic curves are given in Appendix J. Using these methods, annual exceedence probability vs ground motion parameter curves can be developed for any seismic zone. Also presented in Appendix J are the national probabilistic seismic maps, which give ground motion parameters with a 90% probability of not being exceeded in the stated exposure time. These maps were developed for exposure times of 10, 60, and 250 years. The probability

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Table 1. Earthquake source parameters

Event	Date	M^a	M_s^b	M_w^c	M_0^d (10^{27} dyne-cm)	L^e (km)	D^f (km)	Slip type ^g	U^h (m)	T^i (s)	T_0^j (s)	v_r^k (km s ⁻¹)	$\Delta\sigma^l$ (bar)
San Francisco	4/18/06		8.25	7.9	10	430	15	RS	5-7				
Kanto	9/1/23	7.9	8.2	7.9	7.6	130	70	RT	2.1	7	10		21
						85	55	RT	6.7				
Tango	3/27/27	7.5	7.75		0.46	35	13	LS	3	6	2.5	2.3	115
North Izu	11/25/30	7.0	7.1		0.2	20	11	LS	3		1.7		150
Saitama	9/21/33	7.0	6.75		0.068	20	10	LS	1	2	1.6	2.3	59
Saeriku	3/2/33	8.3	8.3	8.4	43	185	100	N	3.3	7	12	3.2	42
Long Beach	3/11/33		6.25		0.028	30	15	RS	0.2	2	2.5	2.3	7
Imperial Valley	5/19/40		7.1		0.48	70	11	RS	2		3.2		55
Tottori	9/10/43	7.4	7.4		0.36	33	13	RS	2.5	3	4.0	2.3	99
Tonankai	12/7/44	7.0	8.2	8.1	15	120	80	T	3.1		9.2		39
Nikawa	1/12/45	7.1	7.1		0.087	12	11	RT	2.2		1.3		140
Nankai	12/20/46	8.1	8.2	8.1	15	120	80	T	3.1		9.2		39
						300	70-120	RT	4-6				
						320	50-140	T	5-18				
Fukui	1/28/48	7.3	7.3		0.33	30	13	LS	2	2	1.9	2.3	100
Tokachi-Oki	3/4/52	8.1	8.3	8.1	17	180	100	T	1.9		14		17
Kern County	7/21/52		7.7		2	60	18	LT	4.6	1	3.6		140
Fairview	12/16/54		7.1		0.13	36	6	RN	2		1.7		100
Chile	5/22/60		8.3	9.5	2400	800	200	T	21		36	3.5	91
						1000	120	T	20				
Kitamino	8/19/61	7.0	7.0		0.09	12	10	RT	2.5	2	1.3	3.0	170
Wasaka Bay	3/27/63	6.9	6.9		0.033	20	8	RS	0.6	2	1.5	2.3	40
North Atlantic I	8/3/63		6.7		0.12	32	11	RS	1		2.2		44
Kurile Islands	10/13/63		8.2	8.5	75	250	140	T	3		17	3.5	28
North Atlantic II	11/17/63		6.5		0.038	27	9	RS	0.48		1.8		24
Spain	3/15/64		7.1		0.13	95	16	T	0.42		3.6	1.4	11
Alaska	3/28/64		8.5	9.2	520	500	300	T	7		35	3.5	22
						600	200	LT	16				
						800	175-290	LT	20				
Niigata	1/16/64	7.5	7.4		3.2	80	30	T	3.3		5.3		66
Rat Island I	2/4/65		7.9	8.7	140	500	150	T	2.5		25	4.0	17
Rat Island II	3/30/65		7.5		3.4	50	80	N	1.2		5.8		33
Parkfield	6/28/66		6.4		0.032	26	7	RS	0.6	0.7	1.6	2.7	32
Aleutian	7/4/66		7.2		0.226	35	12	RS	1.6		2.4		64
Truckee	9/12/66		5.9		0.0083	10	10	RS	0.3		1.2		20
Peru	10/17/66		7.5	8.1	20	80	140	T	2.6		9.6		41
Turkey	7/22/67		7.1		0.83	80	20	RS	1.7		4.7		32
Borrego	4/9/68		6.7		0.063	33	11	RS	0.58		2.2		22
Tokachi-Oki	5/16/68	7.9	8.0	8.2	28	150	100	RT	4.1		12	3.5	37
Saitama	7/1/68	6.1	5.8		0.019	10	6		0.92	1	0.9	3.4	100
Iran	8/31/68		7.3		1	80	20	LS	2.1		4.7		38
Portugal	2/28/69		8.0		5.5	80	50	T	2.5		6.1		53
Kurile Islands	8/11/69		7.8	8.2	22	180	85	T	2.9		12	3.5	28
Gifu	9/9/69	6.6	6.6		0.035	18	10	LS	0.6	1	1.7	2.5	35
Peru	5/31/70		7.8	7.9	10	130	70	N	1.6		8.7	2.5	28
San Fernando	2/9/71		6.6		0.12	20	14	LT	1.4	1	2.0	2.4	62
Nemuro-Oki	6/17/73	7.4	7.7		6.7	60	100	T	1.6		7.5		35
China	7/27/76		8.0	7.5	2	150	15	RS	2.7				

^aMagnitude from local data [e.g., magnitude in "Riva-nenryo" (Annual Table of Scientific Constants, Maruzen Publishing Co., Tokyo) for the Japanese earthquakes].

^bSurface wave magnitude.

^cMagnitude calculated from the seismic moment.

^dSeismic moment in 10^{27} dyne-cm.

^eFault length.

^fFault depth (definition should be slightly changed for a buried fault).

^gN, normal; T, reverse; S, strike-slip; RS right-lateral; LS, left-lateral; RT, reverse with right-lateral; and LT, reverse with left-lateral.

^hFinal slip (average).

ⁱRise time (linear ramp).

^jTheoretical rise time.

^kRupture velocity.

^lStress-drop.

^mEnergy of seismic wave.

ⁿStrain-energy change 1.

^oGeodetic model, principle.

Source: K. Kanahara, *Earthquake Mechanics*, Cambridge University Press, New York, 1981.

Table 1. Earthquake source parameters

M^a	M_s^b	M_w^c	M_0^d (10^{27} dyne-cm)	L^e (km)	D^f (km)	Slip type ^g	U^h (m)	T^i (s)	T_{th}^j (s)	v_r^k (km s ⁻¹)	$\Delta\sigma^l$ (bar)	E_s^m (10^{22} erg)	E_t^n (10^{22} erg)	Remarks
	8.25	7.9	10	430	15	RS	5-7					200	300	
7.9	8.2	7.9	7.6	130	70	RT	2.1	7	10		21			
				85	55	RT	6.7							o
7.5	7.75		0.46	35	13	LS	3	6	2.5	2.3	115	10	4	
7.0	7.1		0.2	20	11	LS	3		1.7		150	2	3	
7.0	6.75		0.068	20	10	LS	1	2	1.6	2.3	59			
8.3	8.3	8.4	43	185	100	N	3.3	7	12	3.2	42			
	6.25		0.028	30	15	ES	0.2	2	2.5	2.3	7			
	7.1		0.48	70	11	RS	2		3.2		55	1	1.5	
7.4	7.4		0.36	33	13	RS	2.5	3	4.0	2.3	99			
7.0	8.2	8.1	15	120	80	T	3.1		9.2		39			
	7.1		0.087	12	11	RT	2.2		1.3		140			
8.1	8.2	8.1	15	120	80	T	3.1		9.2		39			
				300	70-120	RT	4-6							o
				320	50-140	T	5-18							o
7.3	7.3		0.33	30	13	LS	2	2	1.9	2.3	100			
8.1	8.3	8.1	17	180	100	T	1.9		14		17			
	7.7		2	60	18	LT	4.6	1	3.6		140			
	7.1		0.13	36	6	RN	2		1.7		100	6	7	
	8.3	8.5	2400	800	200	T	21		36	3.5	91			
				1000	120	T	20							o
7.0	7.0		0.09	12	10	RT	2.5	2	1.3	3.0	170			
6.9	6.9		0.033	20	8	RS	0.6	2	1.5	2.3	40			
	6.7		0.12	32	11	RS	1		2.2		44			
	8.2	8.5	75	250	140	T	3		17	3.5	28			
	6.5		0.038	27	9	RS	0.48		1.8		24			
	7.1		0.13	95	10	T	0.42		3.6	1.4	11			
	8.5	9.2	520	500	300	T	7		35	3.5	22	300	1000	o
				600	200	LT	16							
				800	175-290	LT	20							o
7.5	7.4		3.2	80	30	T	3.3		5.3		66	11	50	
	7.9	8.7	140	500	150	T	2.5		25	4.0	17			
	7.5		3.4	50	80	N	1.2		5.8		33			
	6.4		0.032	26	7	RS	0.6	0.7	1.6	2.7	32			
	7.2		0.226	35	12	RS	1.6		2.4		64			
	5.9		0.0083	10	10	RS	0.3		1.2		20			
	7.5	8.1	20	80	140	T	2.6		9.6		41			
	7.1		0.83	80	20	RS	1.7		4.7		32			
	6.7		0.063	33	11	RS	0.58		2.2		22			
7.9	8.0	8.2	28	150	100	RT	4.1		12	3.5	37			
6.1	5.8		0.019	10	6		0.92	1	0.9	3.4	100			
	7.3		1	80	10	LS	2.1		4.7		38			
	8.0		5.5	80	50	T	2.5		6.1		53			
	7.8	8.2	22	180	85	T	2.9		12	3.5	28			
6.6	6.6		0.035	18	10	LS	0.6	1	1.7	2.5	35			
	7.8	7.9	10	130	70	N	1.6		8.7	2.5	28			
	6.6		0.12	20	14	LT	1.4	1	2.0	2.4	62			
7.4	7.7		6.7	60	100	T	1.6		7.5		35			
	8.0	7.5	2	150	15	RS	2.7							

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from the seismic moment.
dyne-cm.

on should be slightly changed for a buried fault).

S, strike-slip; RS right-lateral; LS, left-lateral;
al; and LT, reverse with left-lateral.

quake Mechanics, Cambridge University Press, New York, 1981.

^hFinal slip (average).

ⁱRise time (linear ramp time function).

^jTheoretical rise time.

^kRupture velocity.

^lStress-drop.

^mEnergy of seismic waves (approximate).

ⁿStrain-energy change in faulting (approximate).

^oGeodetic model, principally related to land movements.

procedures discussed above can be used for a seismic region to help determine the conservatism of the calculated ground motion values.

Attenuation relationships between each source or fault and the site must be selected for the ground motion acceleration, velocity, and displacement. Attenuation curves for acceleration and velocity in the eastern United States are given in Appendix K. Relations for attenuation of intensity values (MMI) from the source to the site are given, and the conversion of these intensity values to ground motion parameters can be done by the relations given in Appendix E.

At this stage the choice can be made about the nature of the availability of acceleration time histories. If it is desirable not to develop a theoretical earthquake, the next step is the development of the site design response spectra by scaling a standard response spectra by the maximum ground motion parameters as described in Appendix F. Both vertical and horizontal spectra are to be developed. If the choice is made to develop theoretical earthquakes, the following methodology is proposed. The calculational procedure can follow several paths, one being theoretical and the other semitheoretical or semiempirical. The theoretical earthquake is based on having a source mechanism and a geometrical spreading and attenuation mechanism in the computational procedure. The source mechanism is the kinematic model for the slip or movement of the fault displacement during an earthquake as a function of time and position on the fault plane or the focal mechanisms for a source region. The attenuation and spreading mechanism allows calculation at the site of interest of the displacement as a function of time. A more detailed description of the theoretical earthquake development is given in Appendix L. The kinematic models require at least some or all of the source parameters described in Appendix G.

The semitheoretical procedure is based on the use of a theoretical attenuation relationship in which the source amplitude function is statistically fitted to data for the region. The spreading and attenuation mechanism or functional was chosen in a theoretical form. These models are described in Appendix M and may be used to calculate the acceleration at a site as a function of frequency. Also, displacement and velocity can be calculated using these models. To develop a time history using

these models, a standard calculational procedure⁵ that simulates earthquake motions compatible with a prescribed response spectra can be used.

For each source region or fault near the site of interest, these "theoretical" procedures should be used to calculate ground motion time histories. Then select the worst-case time histories and calculate response spectra from each one. It is recommended that the duration be developed using the Trifunac-Brady duration⁶ method corrected for the eastern United States.

Here, another choice can be made to directly develop a synthetic response spectra using a procedure given in Appendix N. Using this procedure, synthetic response spectra can be developed for each plausible focal mechanism using magnitudes, source parameters, and attenuation data. A response spectra can be developed for each focal mechanism and source region close to the site. Then these response spectra can be enveloped to develop the worst-case design response spectra. Again, the Trifunac-Brady duration⁶ method can be used to develop the duration period.

The above procedures are used to develop the SSE that is assumed to occur at a breeder or light-water reactor site as shown in Fig. 1. Methods for developing the ground motion definition for the eastern United States are presented that should prove to meet the needs for this development.

3. GUIDELINES FOR ANALYTICAL PROCEDURES FOR PREDICTING NEAR-FIELD RESPONSE SPECTRA THAT COVER A RANGE OF DAMPING VALUES

The labels "far-field" and "near-field" can be misleading and misunderstood. For the western United States in the field of seismicity, a certain distance is currently used to define near-field, usually 20 km from the source of the earthquake vibratory ground motion. However, the real near-field depends on the geological surroundings of the specific site being analyzed. A theoretical but pleasing definition is as follows:⁷ the far-field is simply all positions that are more than a few wavelengths away from the source, and the near-field is all positions within a small fraction of a wavelength from the source. The wavelengths of interest are those of the compressional and shear waves. These wavelengths can be approximately calculated by

$$\text{compressional wavelength} = \frac{2\pi\alpha}{\omega},$$

$$\text{shear wavelength} = \frac{2\pi\beta}{\omega},$$

where ω is the frequency of the wave, α is the compressional wave velocity, and β is the shear wave velocity. The calculation of the true wavelengths could be difficult and approximate because of variations in the wave velocity with depth in the earth and local soil or geological conditions.⁸ Also, the wavelength depends upon the frequency of the wave, and in earthquakes there are spectra of wave-frequency combinations. However, these simple formulas will give guidance for future theoretical work.

The current practice in development or prediction of near-field response spectra in the western United States is to use a regression analysis of a multitude of different response parameters on instrumental data taken during seismic events. The response spectral amplitudes consist of separate regression analyses of pseudovelocities at frequencies between 0.067 and 25.0 Hz. Response spectra corresponding to certain percentiles are formed in these analyses. In some cases, response spectra from the regression analysis model and spectra from measured records are compared

to indicate the adequacy of the regression analysis. These types of analyses are given in Refs. 8-10 for 5% damped pseudovelocities.

The guidelines for near-field response spectra are shown in Fig. 2. Two methods are to be used to develop the response spectra. One is based on the availability of near-field data, and the other is a theoretical procedure. It is well known that there are few recorded near-field data from the eastern United States for use in statistical analysis;¹⁰ the 1982 aftershocks of the New Brunswick and New Hampshire earthquakes, however, give near-field strong-motion data for $M_b > 4$. As is seen in Fig. 2, if near-field data or strong-motion data for a tectonic region are available, the procedure used in Refs. 8-10 will be used to develop near-field response spectra.

For tectonic provinces or seismic source zones where no strong-motion data have been collected by instrumentation, as is the case in much of the eastern United States regions, simulation studies should be done to develop synthetic seismograms or response spectra for strong motion. The current state of the art allows theoretical or synthetic amplitude spectra to be calculated for simple source mechanisms. To develop synthetic response spectra for a tectonic or seismic source region, the response spectra should be closely matched to the geological structure and to the region's capable faults.

The first step should be a geological study of the tectonic or source region of interest to estimate the geological parameters. All capable faults¹¹ and the potential for surface faulting must be determined. The capable faults are to be determined from historical seismicity and expert opinion. If there has been historical seismic activity along the fault or in the seismic source zone, the relations developed in Appendix G can be used to calculate the potential source parameters needed, such as the seismic moment and fault length, width, and slip. Geological investigations can also be used to estimate the static source parameters.

The next step is to determine the source mechanisms for each capable fault in the fault system. As discussed before, the source mechanism is the kinematic mathematical model for movement along the fault vs time. Kinematic mathematical models have been developed for fault

Fig. 2. Guidelines for near-field response spectra.

motion,^{4,7,12-15} and the best known are the Haskell¹⁶ and Brune¹⁷ models. Recent theoretical developments have allowed researchers to construct fairly realistic seismic models and generate computer simulations of ground motion. A more detailed description of this use of source mechanisms is given in Appendix L.

Semitheoretical procedures (Appendix M) can also be used to calculate the near-field response spectra and apply a simulation method⁵ to develop the time history.

Another choice is to directly develop a synthetic response spectrum as discussed in Appendix N, using the Trifunac-Brady duration⁶ and simulation⁵ methods to develop a synthetic time history.

After the ground motions have been calculated for each capable fault, response spectra for each time history can be developed for a range of damping values of 0 to 20%. These calculated time histories and response spectra can be used directly for the specific site for which they were calculated. If a regression model for the eastern United States is required, the simulated response spectra for this specific site, along with others calculated for the East, can be used in a response spectral amplitude regression analysis.

As shown in Fig. 2, a procedure for calculating near-field motion is given. Such a procedure should be useful where near-field motion is needed for giving both site-specific data and statistically calculated response spectra for the East.

4. OPERATING BASIS EARTHQUAKE

The seismic design procedure for reactor plants in the United States is given in the *Code of Federal Regulations*, 10 CFR 100, Appendix A.¹¹ It requires establishing an SSE that is based on the maximum ground motion at the site and an OBE that in general is based on at least one-half the ground acceleration magnitude of the SSE.

The OBE should be set based on the geological conditions at the site and the recurrence of seismic events in the area. One difficulty with 10 CFR 100 Appendix A is that it contains contradictory statements regarding the OBE. Based on the criteria, the OBE is defined as an earthquake that can reasonably be expected to affect the site during the operating life of the plant. This seems to imply an exposure time of 40 years nominal operating life of a nuclear power plant. However, another section of the criteria requires that the acceleration level of the OBE be at least one-half that of the SSE. Only in areas of very high seismicity do these two distinct criteria for specifying the OBE acceleration level become comparable. Based on the above discussion of the OBE, it should be determined through a probabilistic analysis of the seismicity in the region (see Appendixes H, I, and J). The OBE should be set to specific exposure time rather than 0.5 SSE. For example, based on Poisson processes, a 10% probability of exceedence in a 50-year design life (50 years exposure) would be consistent with 475-year return rate or recurrence interval. Thus, specifying a 475-year recurrence interval for the OBE would be conservative for a seismic event that could reasonably be expected to affect the reactor site during the operating life of the plant.

A departure from setting the OBE to one-half the SSE is permitted within the guidelines of 10 CFR 100 Appendix A¹¹ which states:

If an applicant believes that the particular seismology and geology of a site indicate that some of these criteria, or portions thereof, need not be satisfied, the specific sections of these criteria should be identified in the license application and supporting data to justify clearly such departures should be presented.

Probabilistic seismic analysis is being used in the design of many critical structures and is an accepted practice today. Setting the OBE by probabilistic analysis will be more realistic for the operating life of the plant without affecting the safety of the public since the plant is designed to withstand the SSE without undue risk to the public.

5. CLOSURE

Guidelines for ground motion definition both near-field and far-field for the eastern United States have been developed with specific recommendations where they can be made. A proposed "new" method for developing the OBE is given and is felt to be realistic for the eastern region of the country. These guidelines should prove useful in the development of seismic design requirements for future reactors.

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REFERENCES

1. P. D. Smith, "Observations on Seismic Probabilistic Risk Assessments," *Seismic Events Probabilistic Risk Assessments*, ASME PVP-Vol. 79, June 1984.
2. D. Veneziano, "Errors in Probabilistic Seismic Hazard Analysis," in *State-of-the-Art for Assessing Earthquake Hazards in the United States*, Miscellaneous Paper S-73-1-18, U.S. Army Engineering Waterways Experiment Station, January 1982.
3. *Earthquake History of the United States*, Publication 41-1, U.S. Department of Commerce, National Oceanic and Atmospheric Administration and U.S. Department of the Interior, Geological Survey, 1982.
4. K. Kasahara, *Earthquake Mechanics*, Cambridge University Press, New York, 1981.
5. D. Gasparini and E. H. Vanmarcke, "Evaluation of Seismic Safety of Buildings, Report No. 2," *Simulated Earthquake Motions with Prescribed Response Spectra*, Massachusetts Institute of Technology, PB-252-896, January 1976.
6. *Definition of Design Earthquake Vibratory Ground Motion Recommended Guidelines*, SAN-1011-124, Agabian Associates, March 1980.
7. K. Aki and P. G. Richards, *Quantitative Seismology, Theory, and Methods, Volumes I and II*, W. H. Freeman and Co., San Francisco, 1980.
8. *Statistical Analysis of Earthquake Ground Motion Parameters*, NUREG/CR-1175, Shannon & Wilson, Inc., and Agabian Associates, U.S. Nuclear Regulatory Commission, December 1979.
9. H. S. Tsao, *Correlation of Peak Earthquake Ground Acceleration in the Very Near-Field*, SAN-1011-125, Agabian Associates, April 1980.
10. *Statistical Analysis of Response Spectral Amplitudes Including Near-Field Data*, DOE/SF/01011-129, Agabian Associates, November 1981.
11. *Seismic and Geologic Siting Criteria for Nuclear Power Plants*, Appendix A, 10 CFR Pt. 100.
12. A. K. Mal, T. Kundu, and P. C. Xu, *Ground Motion Calculations, Earthquake Motion and Its Effects on Structures*, ASME Special Publication AMD - Vol. 53, ASME Winter Annual Meeting, Phoenix, Ariz., November 14-19, 1982.
13. B. A. Bolt, ed., "Seismology: Body Waves and Sources," Vol. 12 of *Methods in Computational Physics, Advances in Research and Applications*, Academic Press, New York, 1972.

14. R. J. Apsel, D. M. Hadley, and R. S. Hart, *Effects of Earthquake Rupture Shallowness and Local Soil Conditions on Simulated Ground Motions*, NUREG/CR-3102, Lawrence Livermore Laboratory, U.S. Nuclear Regulatory Commission, March 1983.
15. K. Aki, "Earthquake Source Mechanism," *Earthquake Source Modeling, Ground Motion, and Structural Response*, ASME, PVP-Vol. 80, New York, 1984, pp. 1-12.
16. N. A. Haskell, "Elastic Displacement in the Near-Field of a Propagating Fault," *Bull. Seismol. Soc. Am.* 59(2), 865-908 (April 1969).
17. J. N. Brune, "Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes," *J. Geophys. Res.* 75(26), 4997-5009 (September 10, 1970).

Appendix A

TECTONIC PROVINCES

The eastern United States can be divided into a number of distinct regions on the basis of different geologic, seismic, and/or other geophysical characteristics within each region. A map showing these regions is termed a tectonic, or seismotectonic province map, depending on whether the differences in seismicity occurring in different parts of the country are considered. The data used to define tectonic provinces include the types and ages of geologic structures found and the character of the earth's gravity and magnetic fields within different regions. A generalized tectonic map¹ of North America is presented in Fig. A.1. This particular map is based primarily on differences in the near-surface geology. A map that also incorporates seismicity and other geophysical data would likely contain more subdivisions than are depicted here.

An appropriate tectonic regionalization is important for an accurate definition of earthquake ground motion for the purpose of engineering design. In addition, the concept of tectonic provinces is embedded in the regulations that govern the construction of nuclear reactors. For regulatory purposes (10 CFR 100), it is necessary to consider the nature of the seismicity within the tectonic province containing the plant site. However, the construction of a seismotectonic map involves the interpretation of available geologic and geophysical data. Such interpretations are subject to change as additional data become available, as new theories are presented to explain the observed patterns of seismicity and the forces involved in the development of the continental crust throughout geologic time, and as different scientists reexamine existing data. Thus, seismotectonic maps are subject to change.

It is important to distinguish between tectonic maps that are based primarily on near-surface geologic characteristics and those that incorporate other data. Most earthquakes, particularly the larger ones, occur at considerable depth within the crust. In some parts of the eastern United States the surface material may be viewed as a relatively thin

Fig. A.1. Tectonic map of North America. Source: W. K. Hamblin and J. D. Howard, *Exercises in Physical Geology*, Burgess Publishing Co., Minneapolis, Minn., 1975.

veneer, and the geologic characteristics of this layer may be quite different from those of the underlying layer that contains the earthquake foci. Generally, the deeper portions of the crust are not subject to direct observation so that geophysical data obtained at the surface, or by remote sensing techniques which utilize aircraft or satellites, must be used to distinguish between the different regions thought to exist at depth.

Reference

1. W. K. Hamblin and J. D. Howard, *Exercises in Physical Geology*, Burgess Publishing Co., Minneapolis, Minn., 1975.

Appendix B

SEISMIC SOURCE ZONES IN THE CONTIGUOUS UNITED STATES

This appendix gives one of the latest tabulations of seismic source zones for the contiguous United States.¹ The zones are shown in Figs. B.1 and B.2. The b-value and the number of intensity V earthquakes per year in each zone are listed in Table B.1. For each zone the maximum intensity was determined from consideration of (1) the largest historical earthquake that had occurred, (2) the tectonic setting of the particular zone, (3) expert opinion, and (4) combinations of the above sources of information. The maximum magnitude is an estimate of the largest earthquake possible in the region. In general, these are expressed as M_b magnitudes. For shocks less than 6-3/4, M_L is used, whereas for larger earthquakes M_b is used.

Reference

1. S. T. Algermissen et al., *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States*, United States Department of Interior, Geological Survey, Open-File Report 82-1033, 1982.

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Fig. B.1. Seismic source zones in contiguous United States (other than those shown in Fig. B.2). Numbers in source zones are used to identify each zone in discussion in text and in Table B.1.

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Fig. B.2. Seismic source zones in western California and adjacent offshore areas. Numbers in source zones are used to identify each zone in Table B.1. Zones 1-39 are preceded by "c" in Table B.1.

Table B.1. Seismic parameters
for source zones

Zone No. ^a	MMI (V/year)	b _I	Maximum magnitude M ^b
p001	0.11010	-0.40	7.3
p002	0.43510	-0.40	7.3
p003	0.12440	-0.54	7.3
p004	0.34840	-0.62	7.3
p005	0.12390	-0.62	7.3
p006	0.02831	-0.62	7.3
p008	0.01642	-0.42	7.3
p009	0.20850	-0.28	7.9
p010	0.45200	-0.28	7.9
p011	0.96370	-0.28	7.9
p012	0.37090	-0.28	7.9
p013	0.69020	-0.28	7.9
p014	0.10940	-0.42	7.3
p015	0.34480	-0.42	7.3
p016	0.04926	-0.42	7.3
p017	0.87860	-0.28	7.9
p018	0.18810	-0.54	7.3
p019	0.04090	-0.54	7.3
c001	0.62770	-0.42	7.3
c002	0.15700	-0.42	7.3
c003	0.31960	-0.42	7.3
c004	0.31960	-0.42	7.3
c005	0.04843	-0.42	6.1
c006	0.15700	-0.42	7.3
c007	0.15700	-0.42	7.3
c008	0.04740	-0.42	6.1
c009	0.04843	-0.42	6.1
c010	0.18190	-0.42	6.1
c011	0.77010	-0.42	7.3
c012	0.19050	-0.42	7.3
c013	0.35840	-0.42	7.3
c014	0.91990	-0.66	7.9
c015	1.49200	-0.45	7.9
c016	0.22560	-0.51	7.9
c017	0.02760	-0.48	7.3
c018	1.09200	-0.49	7.3
c019	0.31980	-0.42	6.7
c020	0.19280	-0.42	6.1
c021	0.10880	-0.42	6.1
c022	0.02422	-0.42	6.1
c023	0.11650	-0.37	7.9
c024	1.97000	-0.43	8.5
c025	0.05085	-0.55	7.3

Table B.1 (continued)

Zone No. ^a	MMI (V/year)	b _I	Maximum magnitude M ^b
c026	0.09145	-0.55	7.3
c027	0.03437	-0.37	7.3
c028	0.13010	-0.37	7.3
c029	0.02350	-0.37	7.3
c030	0.03630	-0.42	6.7
c031	0.47580	-0.51	6.7
c032	0.55190	-0.45	7.9
c033	0.23070	-0.37	7.9
c034	0.67120	-0.51	7.9
c035	0.02325	-0.60	7.3
c036	0.35220	-0.59	6.7
c037	0.81950	-0.51	6.1
c038	0.82680	-0.54	7.9
c039	0.35810	-0.45	7.9
c040	0.15820	-0.42	6.1
c041	0.08448	-0.37	7.9
001	0.22700	-0.73	7.3
002	0.03600	-0.73	7.3
003	0.08800	-0.73	6.1
004	0.22700	-0.54	7.3
005	0.09100	-0.73	7.3
006	0.13500	-0.73	7.3
007	0.41900	-0.73	7.3
008	0.21100	-0.73	6.1
009	0.19400	-0.54	6.1
010	0.20800	-0.54	7.3
011	0.55100	-0.64	7.3
012	0.34900	-0.64	7.3
013	0.05500	-0.64	7.3
014	0.49000	-0.73	7.3
015	0.01800	-0.73	6.7
016	0.14600	-0.73	6.1
017	0.69300	-0.59	7.3
018	0.26100	-0.54	7.3
019	0.11717	-0.54	7.3
020	1.84900	-0.64	7.3
022	0.19600	-0.64	6.1
023	0.15350	-0.54	7.3
024	0.27400	-0.64	7.3
025	0.16800	-0.64	6.1
026	0.47700	-0.64	6.1
027	0.11100	-0.64	5.5
029	1.31900	-0.64	7.3
030	0.58800	-0.64	7.3

Table B.1 (continued)

Zone No. ^a	MMI (V/year)	b _I	Maximum magnitude M ^b
031	1.82685	-0.54	7.3
032	0.48114	-0.54	6.1
033	0.08557	-0.54	6.1
034	0.62380	-0.54	7.3
035	0.20070	-0.54	7.3
036	0.01800	-0.58	6.1
037	0.05100	-0.58	7.3
038	0.80600	-0.58	7.3
039	0.12000	-0.58	7.3
040	0.29100	-0.58	7.3
041	0.24400	-0.73	7.3
042	0.01800	-0.73	6.1
043	0.04600	-0.73	7.3
044	0.11300	-0.73	6.1
045	0.45600	-0.73	6.1
046	0.01274	-0.73	6.1
047	0.00427	-0.73	6.1
048	0.00329	-0.73	6.1
049	0.01663	-0.73	6.1
050	0.17000	-0.73	6.1
051	0.01706	-0.73	6.1
052	0.19000	-0.58	7.3
053	0.03600	-0.58	7.3
054	0.01800	-0.58	6.1
055	0.67300	-0.58	7.3
056	0.17700	-0.58	6.1
057	0.66200	-0.58	7.3
058	0.19800	-0.58	7.3
059	0.19200	-0.58	6.1
060	0.03600	-0.58	6.1
061	0.08900	-0.58	7.3
062	0.03600	-0.58	6.1
063	0.12900	-0.58	6.1
064	0.34400	-0.58	7.3
065	0.15200	-0.58	6.1
066	0.01800	-0.73	6.1
067	0.07715	-0.46	6.1
068	0.02894	-0.46	6.1
069	0.00588	-0.46	6.1
070	0.03552	-0.46	6.1
071	0.01176	-0.46	6.1
072	0.02026	-0.46	6.1
073	0.02353	-0.46	6.1
074	0.00270	-0.46	6.1
075	0.06510	-0.46	6.1

Table B.1 (continued)

Zone No. ^a	MMI (V/year)	b _I	Maximum magnitude M ^b
076	0.14742	-0.46	6.1
077	0.03469	-0.46	6.1
078	0.04389	-0.46	6.1
079	0.03082	-0.46	6.1
080	0.02987	-0.46	6.1
081	0.02044	-0.46	6.1
082	0.03552	-0.46	6.1
083	0.00996	-0.46	6.1
084	0.04117	-0.46	6.1
085	0.03802	-0.46	6.1
086	0.04626	-0.46	6.1
087	0.29865	-0.46	8.5
088	0.09703	-0.46	6.1
089	0.15689	-0.46	6.1
090	0.06103	-0.46	6.1
091	0.00644	-0.46	6.1
092	0.02661	-0.46	6.1
093	0.02680	-0.46	6.1
094	0.10835	-0.46	6.1
095	0.05901	-0.46	6.1
096	0.02675	-0.46	6.1
097	0.01156	-0.46	6.1
098	0.01215	-0.46	6.1
099	0.24830	-0.50	7.3
100	0.42290	-0.50	7.3
101	0.18720	-0.50	7.3
102	0.09532	-0.50	7.3
103	0.33150	-0.50	7.3
104	0.05544	-0.50	7.3
106	0.01952	-0.50	6.7
107	0.19100	-0.50	7.3
108	0.29390	-0.50	6.7
109	0.10650	-0.50	7.9
110	0.30220	-0.50	7.9
111	0.32430	-0.50	7.9
112	0.01532	-0.50	6.7
113	0.07432	-0.50	6.7
114	0.00754	-0.50	6.7
115	0.05834	-0.50	7.3
116	0.06783	-0.50	6.7
117	0.03950	-0.50	7.3
118	0.01334	-0.50	7.3

^aThe zones are shown in Figs. B.1 and B.2.

^bSee text for definition of M.

Appendix C

EARTHQUAKE MAGNITUDE

The earthquake magnitude is basically a relative scale that defines a standard size earthquake and rates others in a relative manner by their maximum amplitude under identical observational conditions. The definition for the Richter or local magnitude is¹

$$M_L = \log (A/A_0) , \quad (C.1)$$

where A_0 is the maximum trace excursion of a zero magnitude earthquake. The standard or zero-magnitude earthquake is one that results in a maximum trace excursion of 1 mm on a Wood-Anderson seismograph at an epicentral distance of 100 km. A is the maximum trace excursion on the same seismograph of the measured event.

In recent years, many local seismic networks have been set up to study small earthquakes and microearthquakes. Many of these networks use high-gain, short-period vertical instruments and do not include Wood-Anderson seismographs. The use of these high-gain instruments allows wave amplitudes to be measured for the smallest local earthquakes but requires a modification to the method for determining magnitude.

A different approach, one which uses an empirical formula for estimating the magnitude of local earthquakes using signal durations, has been established for the National Center for Earthquake Research.^{2,3} The magnitude is given by

$$M_L = -0.87 + 2 \log \tau + 0.0035 R , \quad (C.2)$$

where τ is the signal duration in seconds and R is the epicentral distance in kilometers. This magnitude M_L is called the Richter or local magnitude. The local magnitude can only be used for shallow local earthquakes where $R < 600$ km.

Further modifications have since been introduced to the magnitude definition so that it is now possible to measure the size of a distant or deep earthquake. The magnitudes used for these purposes are the surface

wave magnitude M_g and the body wave magnitude m_b . For $R > 600$ km, seismograms are dominated by surface waves with a period of ~ 20 s. These waves are Love and Rayleigh waves. Thus, the surface wave magnitude⁴ M_g has been introduced for the teleseismic distances (>2000 km) as

$$M_g = \log A + \alpha \log R + \beta, \quad (C.3)$$

where A (μm) represents the maximum amplitude of the horizontal ground displacement for surface waves with a 20 s period. The constants α and β are determined empirically by considering several reference earthquakes of known magnitude. In practice, the constants determined by various researchers scatter about the original data of Gutenberg⁵ ($\alpha = 1.656$, $\beta = 1.818 + C$, where C is a station constant), reflecting the effect of local conditions. The epicentral distance R is in kilometers. Both the M_L and M_g relations apply only to shallow earthquakes with depths less than ~ 60 km.

The surface waves produced by deeper earthquakes do not show the same relation between $\log A$ and R as the shallow earthquakes. Gutenberg and Richter⁶ investigated the variation of both compressional and shear body wave phases with distance for shallow and deep earthquakes. On the basis of these data they proposed a body wave magnitude:

$$m_b = \log (A/T) + Q(h,R), \quad (C.4)$$

where T is the period (in seconds) of the measured wave and A represents ground amplitude (in micrometers) computed from the trace measurement and calibration factors for the particular instrument used. $Q(h,R)$ is a parameter which is given empirically and is a function of depth h of the seismic focus and the epicentral distance R .

Nuttli developed an m_b scale based on the measured amplitude of L_g waves,⁷ which are large amplitude arrivals having predominantly traverse motion. These waves propagate within the continental crust at velocities close to the average shear velocity in the upper part of the crust. These waves, observed only when the path is entirely continental, are cut off abruptly when the path has even a small oceanic segment. The L_g waves

are generally considered channel waves in the crust which are superimposed on the long-period surface waves. Using measured L_g waves in the central United States, Nuttli computed $m_b(L_g)$ magnitude by

$$m_b(L_g) = 3.75 + 0.90 \log R + \log (A/T) \text{ for } 0.5^\circ < R < 4^\circ, \quad (C.5a)$$

$$m_b(L_g) = 3.30 + 1.66 \log R + \log (A/T) \text{ for } 4^\circ < R < 30^\circ, \quad (C.5b)$$

where A is maximum ground amplitude (zero to peak, in micrometers) of L_g waves, and R is the epicentral distance in degrees. One degree is equivalent to a 111.12-km distance in the earth's surface.

The magnitudes of earthquakes in the eastern United States are generally measured in terms of m_b and $m_b(L_g)$. For a few large earthquakes, M_s is used. In the western United States, M_L is generally used whereas m_b and M_s are sometimes used. Empirical relations between the different magnitude scales have been developed by several researchers for the eastern United States, some of which are listed below. Nuttli⁸ developed the following relation for the eastern and western regions of the United States:

$$m_b = 0.98 M_L - 0.29. \quad (C.6)$$

Wyss and Habermann⁹ proposed the following method

$$\begin{aligned} M_s &= M_L, \\ M_s &= 1.8 m_b - 4.3 \quad (1963 \text{ to } 1980), \\ M_s &= 1.8 m_b - 5.2 \quad (\text{pre-1963}), \end{aligned} \quad (C.7)$$

for worldwide data. The method for determining m_b was revised in 1963. Chung and Bernreuter³ developed the following relation for the eastern United States:

$$m_b = 2.37 + 0.6 M_s. \quad (C.8)$$

Midplate earthquakes, which are defined as having their epicenter at least 500 km from the plate margins, occur within the continental interiors and are characterized by large damage areas. The 1886 South

Carolina and the 1811 and 1812 New Madrid events are classified as midplate earthquakes. Nuttli developed the following relations¹⁰ for world-wide data from midplate earthquakes:

$$M_s = 1.0 m_b - 1.15 \text{ for } m_b < 4.5 ,$$

$$M_s = 2.0 m_b - 5.65 \text{ for } 4.5 < m_b < 7.0 . \quad (C.9)$$

Figure C.1 shows the relationship of Eq. (C.9) compared with the data from which it was developed.

For eastern earthquakes, the magnitude scales developed from present-day event data are body wave m_b or surface wave M_s magnitudes; these scales are the most important for engineering purposes.

References

1. C. F. Richter, "An Instrumental Earthquake Magnitude Scale," *Bull. Seismol. Soc. Am.* 25, 1-35 (1935).
2. W. H. K. Lee, R. E. Bennett, and K. L. Meagher, *A Method of Estimating Magnitude of Local Earthquakes from Signal Duration*, USGS Open-File Report, U.S. Department of Interior, U.S. Geological Survey, Menlo Park, Calif., p. 28, 1972.
3. D. H. Chung and D. L. Bernreuter, *Regional Relationships Among Earthquake Magnitude Scales*, NUREG/CR-1457, Lawrence Livermore Laboratory, 1980.
4. B. Gutenberg and C. F. Richter, "On Seismic Waves," *Gerland Beitr. Geophys.* 47, 73-131 (1936).
5. B. Gutenberg, "Magnitude Determination for Deep-Focus Earthquakes," *Bull. Seismol. Soc. Am.* 35, 117-30 (1945).
6. B. Gutenberg and C. F. Richter, "Earthquake Magnitude, Intensity, Energy and Acceleration," *Bull. Seismol. Soc. Am.* 46, 105-45 (1956).
7. O. W. Nuttli, "Seismic Wave Attenuation and Magnitude Relations for Eastern North America," *J. Geophys. Res.* 78, 876-85 (1973).
8. O. W. Nuttli, "The Relation of Sustained Maximum Ground Acceleration and Velocity to Earthquake Intensity and Magnitude," Report 16 of *State-of-the-Art for Assessing Earthquake Hazards in the United States*, U.S. Army Corps of Engineers Waterways Experiment Stations, Vicksburg, Miss., Misc. Paper S-73-1, November 1979.
9. M. Wyss and R. E. Habermann, "Conversion of m_b to M_b for Estimating the Recurrence Time of Large Earthquakes," *Bull. Seismol. Soc. Am.* 72(5), 1651-62 (October 1982).
10. O. W. Nuttli, "Average Seismic Source-Parameter Relations for Mid-Plate Earthquakes," *Bull. Seismol. Soc. Am.* 73(2), 519-35 (April 1983).

Appendix D

INTENSITY SCALES

Since the destructiveness of earthquakes is of primary interest, descriptive systems for categorizing the damage experienced, referred to as intensity scales, have been in existence for over 400 years. The measurement¹ of earthquake intensities by human perception was attempted early in the Gastaldi Scale (1564), the de Poardi Scale (1627), the Pignatoro Scale (1783), and the K. Sekiya Scale (1884). In the United States, the Rossi-Forel Scale (1883) was used prior to the early 1930s.² The Modified Mercalli Intensity Scale (MMI) was published in 1931² and has been used universally in this country since shortly after that time. This scale does not provide direct quantitative information on earthquake ground motion, but is a subjective rating system based on observed damage to the ground and slopes and to buildings and other man-made structures following an earthquake. A brief description of the scale is given in Table D.1. The scale is compared with the older and now obsolete Rossi-Forel Scale. This version of the MMI scale is called the abridged³ scale, and intensities were assigned using this scale for earthquakes in the eastern United States through 1974. In 1975, the U.S. Geological Survey and the National Oceanic and Atmospheric Administration adopted the unabridged MMI scale for assigning earthquake intensities³ (see Table D.2). Although both scales were published in the same paper, a difference in the two scales appears at the intensity V and VI levels. For intensity V, the abridged scale states: "a few instances of cracked plaster . . .," whereas the unabridged scale places "cracked plaster" at the intensity VI level. These differences will be reconciled in the new edition of Ref. 3. It is evident from these two tables that intensities assigned by these scales are greatly affected by many factors other than the intensity of ground motion. These factors include the quality of construction, topography, and local soil conditions. It is therefore difficult to extrapolate quantitative information on ground motion from MMI data.

Table D.1. Modified Mercalli Intensity Scale of 1931
(Abridged)

-
- I. Not felt except by a very few under especially favorable circumstances. (I Rossi-Forel Scale.)
 - II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to III Rossi-Forel Scale.)
 - III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale.)
 - IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V Rossi-Forel Scale.)
 - V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale.)
 - VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale.)
 - VII. Everybody runs outdoors. Damage *negligible* in buildings of good design and construction; *slight to moderate* in well built ordinary structures; *considerable* in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars. (VIII—Rossi-Forel Scale.)
 - VIII. Damage *slight* in specially designed structures; *considerable* in ordinary substantial buildings, with partial collapse; *great* in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII+ to IX Rossi-Forel Scale.)
 - IX. Damage *considerable* in specially designed structures; well-designed frame structures thrown out of plumb; *great* in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel Scale.)
 - X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale.)
 - XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
 - XII. Damage *total*. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.
-

Source: H. O. Wood and F. Neumann, "Modified Mercalli Intensity Scale," *Bull. Seismol. Soc. Am.* 21(4), 277-83 (December 1931).

Table D.2. Modified Mercalli Intensity Scale of 1931
(Unabridged)

-
- I. Not felt — or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.
 - II. Felt indoors by few, especially on upper floors, or by sensitive or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially where delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway; doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.
 - III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.
 - IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy, or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.
 - V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated. Awakened many, or most. Frightened few—slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows—in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

Table D.2 (continued)

-
- VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang—church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks in chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.
- VII. Frightened all—general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel streambanks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roofline (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.
- VIII. Fright general—alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly—branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse; racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

Table D.2 (continued)

-
- IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.
 - X. Cracked ground, especially where loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and streambanks. Landslides considerable from riverbanks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.
 - XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments, often for long distances. Few, if any, (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in earth completely out of service.
 - XII. Damage total—practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of riverbanks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.
-

Source: H. O. Wood and F. Neumann, "Modified Mercalli Intensity Scale," *Bull. Seismol. Soc. Am.* 21(4), 277-83 (December 1931).

Intensity data are normally displayed graphically in the form of a map that depicts the pattern of isoseismal regions, which encompass the different intensity levels resulting from an earthquake. An isoseismal region is an area that experienced the same level of damage or MMI intensity. Figures D.1 and D.2 show isoseismal maps for two of the largest earthquakes that have historically occurred in the eastern United States. Shown in Figs. D.3 and D.4 are two of the latest eastern earthquakes — Sharpsburg, Kentucky, and New Brunswick, Maine.

Care must be exercised in reading isoseismal maps. Most commonly, the isoseismal regions depicted are labeled with intensity values, but the lines between different regions are unlabeled (Figs. D.1, D.3, and D.4). Sometimes the lines are labeled (Fig. D.2), in which case the indicated intensity applies to the entire region inside the line. It is important to understand that the MMI intensity does not change within one of the regions on the map. Further it is not permissible to interpolate between the contours depicted on an isoseismal map to obtain fractional values of intensity. This can be verified by comparing the descriptions of intensity III effects to those of intensity IV. It makes no sense to discuss intensity III 1/2. Failure to consider the nature of MMI data properly can lead to serious errors in ground motion prediction.

In regions where there are no strong motion earthquake acceleration records, the earthquake vibratory ground motion that can be expected to occur at a proposed site is frequently estimated from MMI intensity data from historical regional earthquakes. The procedure requires the development of MMI/distance attenuation relationships from regional historical earthquakes and the use of MMI/peak ground motion conversion relationships. The overall procedure is only approximate, with the possibility of significant errors generally being associated with the development of the attenuation and peak ground motion relationships.

Isoseismal maps have been prepared for almost all earthquakes in the United States for/or by the National Oceanic and Atmospheric Administration, Environmental Data and Information Service.³

Fig. D.1. Isoseismal map of eastern United States contoured to show broad regional patterns of reported intensities for 1886 Charleston earthquake. Contoured intensity levels are shown in Roman numerals (Ref. 4).

Fig. D.2. Generalized isoseismal map of New Madrid, Missouri, earthquake of December 16, 1811 (Ref. 5).

The general procedure for developing MMI/distance attenuation relationship is first to collect isoseismal maps for several regional earthquakes. Then, the distances from the estimated epicenters to each isoseismal are measured along a series of radii drawn from the epicenters for each map. After the collection of the distance data for each isoseismal, the average, the mean, or other statistical procedures are used to arrive at the "value" of distance for the MMI scale value.⁸⁻¹⁰ The above is repeated for each isoseismal and then an MMI/distance relationship is developed as either a graphical curve or mathematical relation.

MMI/ground motion relationships are based on data taken during earthquake events. These include strong motion data and other instrumented

Fig. D.3. Isoseismal map for Sharpsburg, Kentucky, earthquake of July 27, 1980 (Ref. 6).

data. Unfortunately, most instrumented data in the United States are from California and not the eastern regions. As a result, there is some uncertainty as to whether these relations are applicable to the eastern United States. The attenuation and ground motion relationships are discussed and presented in Appendix K.

Intensity scales as discussed earlier are not a direct quantitative measure of the strength of earthquake ground motion but represent a subjective rating based on the observed level of damage to the ground, earth

Fig. D.4. Isoseismal map for New Brunswick, Maine, earthquake of January 9, 1982 (Ref. 7).

slopes, buildings, and other man-made structures. Many factors other than ground motion determine the assigned MMI level, and an excellent discussion of these factors is given in Ref. 8.

References

1. K. Kanai, *Engineering Seismology*, University of Tokyo Press, Tokyo, 1983, pp. 23-38.
2. *Definition of Design Earthquake Vibratory Ground Motion Recommended Guidelines*, Agbabian Associates, 1980, pp. 2-38-39.
3. *Earthquake History of the United States*, Publication 41-1, U.S. Department of Commerce, National Oceanic and Atmospheric Administration and U.S. Department of Interior, Geological Survey, 1982.
4. G. A. Bollinger, *U.S. Geological Survey Professional Paper 1928*, 1977, pp. 17-32.

5. O. W. Nuttli, "The Mississippi Valley Earthquakes of 1811 and 1812, Intensities, Ground Motion and Magnitudes," *Bull. Seismol. Soc. Am.* 63(1), 227-48 (February 1973).
6. F. J. Mauk, D. Christensen, and S. Henry, "The Sharpsburg, Kentucky, Earthquake 27 July 1980, Main Shock Parameters and Isoseismal Maps," *Bull. Seismol. Soc. Am.* 72(1), 221-36 (February 1982).
7. O. W. Nuttli, R. Rodriguez, and R. B. Herrmann, *Strong Ground Motion Studies for South Carolina Earthquakes*, NUREG/CR-3755, Lawrence Livermore National Laboratory, April 1984.
8. D. P. Reddy, ed., *Special Topics in Earthquake Ground Motion*, Vol. 1, *Seismic Design Technology for Breeder Reactor Structures*, Agbabian Associates, DOE/SF/d1011-T25 (Vol. 1), April 1983.
9. G. A. Bollinger, *The Giles County, Virginia, Seismic Zone-Configuration and Hazard Assessment Proceedings of Earthquakes and Earthquake Engineering. The Eastern United States*, September 14-16, 1981, Knoxville, Tennessee, Vol. 1, 1981, pp. 277-308.
10. J. G. Anderson, "On the Attenuation of Modified Mercalli Intensity with Distance in the United States," *Bull. Seismol. Soc. Am.* 68(4), 1147-79 (August 1978).

Appendix E

CONVERSION OF MAGNITUDE OR INTENSITY
TO GROUND MOTION PARAMETERS

In earthquake-resistant design, the accepted practice is to express the MMI intensity or magnitude at the site in terms of the peak ground motion parameters (acceleration, velocity, and displacement). Empirical intensity or magnitude relations are used to scale the design response spectra to perform the conversion. The first such relationship was empirically developed by Gutenberg and Richter¹ in 1942 and is given by

$$\log a = 1/3 I_s - 0.5 , \quad (E.1)$$

where a is the maximum acceleration in centimeters per square second and I_s is the site MMI. This relationship was only based on a small sample of data, and in 1956, Gutenberg and Richter redefined their relationship using more data. This relationship and one developed by Newmann are given in Fig. E.1. Tables E.1 and E.2 list more up-to-date empirically developed relationships between MMI and peak acceleration, and MMI and peak velocity. Few relationship have been developed between MMI and peak displacement. Reference 6 gives the following relations:

for horizontal displacement

$$\ln(d) = -1.22 + 0.44 I_s , \quad (E.2)$$

and for vertical displacement

$$\ln(d) = -2.60 + 0.55 I_s , \quad (E.3)$$

where d is in centimeters. The relations given above and in Tables E.1 and E.2 were developed from western United States and worldwide data and could differ from eastern United States ground motion significantly. However, at present these are the only up-to-date conversion relations between MMI and ground motion parameters.

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Fig. E.1. Intensity and acceleration relations developed by Gutenberg and Richter (Ref. 2) and Neumann (Ref. 3).

For the South Carolina region⁹ Rodriguez developed the relation for the peak horizontal acceleration

$$\ln (a) = -0.55 + 1.04 m_b . \quad (E.4)$$

This relation was developed from data in the eastern region of the United States. Since much data in the east are now being developed using body wave magnitude m_b , relationships between m_b and MMI for eastern regions have been tabulated in Table E.3. By using these relations, values for m_b can be converted to MMI and relations given in the tables and in Eqs. (E.2) and (E.3) can be used to calculate the ground motion parameters.

Table E.1. Peak acceleration — MMI relationships in centimeters per second

$$[\ln(a) = b + CI_s + dS]^a$$

Developer	Reference	Horizontal			Vertical		
		b	c	d	b	c	d
LLNL ^b	4	-1.69	0.86				
LLNL ^c	4	-2.32	0.96				
Murphy and O'Brien	5	0.60	0.55		-0.92	0.65	
Trifunac and Brady	6	-0.032	0.69		-0.42	0.69	
Trifunac	7	-0.19	0.67	0.33			
McGuire ^d	8	-0.83	0.85				
McGuire ^e	8	0.27	0.6				

^aUsed for site type (rock or soil).

S = 0 (alluvium)

S = 1 (intermediate rock sites)

S = 2 (basement rock sites).

^b $I_s > I_{s0} > IV$.

^c $I_s > I_{s0} > V$.

^dMedium site.

^eSoft site.

Table E.2. Peak velocity — MMI relationships in centimeters per second

$$[\ln(v) = b + CI_s + dS]^a$$

Developer	Reference	Horizontal			Vertical		
		b	c	d	b	c	d
Trifunac and Brady	6	-1.45	0.58		-2.53	0.65	
Trifunac	7	-2.25	0.67	0.032			
McGuire ^b	8	-4.02	0.952				
McGuire ^c	8	-1.51	0.543				

^aUsed for site type (rock or soil).

S = 0 (alluvium)

S = 1 (intermediate rock)

S = 2 (basement rock sites).

^bMedium sites.

^cSoft sites.

Table E.3. MMI and m_b relationships in the eastern United States

$$(I_s = a m_b + b \pm \sigma)$$

Region	Reference	a	b	σ
Eastern United States	9, 10	1.98	-3.41	0.16
Central United States	9, 10	2.07	-3.97	0.27
South Carolina	9	1.81	-1.95	1.24
New Brunswick, Maine	9	1.96	-5.17	0.09
Sharpsburg, Kentucky	9	1.46	-0.58	0.60

References

1. B. Gutenberg and C. F. Richter, "Earthquake Magnitude, Intensity, Energy, and Acceleration," *Bull. Seismol. Soc. Am.* 32(3), 163-91 (July 1942).
2. B. Gutenberg and C. F. Richter, "Earthquake Magnitude, Intensity, Energy and Acceleration," *Bull. Seismol. Soc. Am.* 46, 105-45 (1956).
3. F. Neumann, *Earthquake Intensity and Related Ground Motion*, Washington Univ. Press, Seattle, Wash., 1954, p. 40.
4. D. L. Bernreuter et al., *Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results for Ten Sites*, NUREG/CR-3756, Lawrence Livermore National Laboratory, April 1984.
5. J. R. Murphy and L. J. O'Brien, *Analysis of a Worldwide Strong Motion Data Sample to Develop an Improved Correlation Between Peak Acceleration, Seismic Intensity and Other Physical Parameters*, NUREG-0402, Computer Sciences Corporation, 1977.
6. M. D. Trifunac and A. G. Brady, "On the Correlation of Seismic Intensity Scale with the Peaks of Recorded Ground Motion," *Bull. Seismol. Soc. Am.* 65, 139-62 (1975).
7. M. D. Trifunac, "A Note on the Range of Peak Amplitudes of Recorded Accelerations, Velocities and Displacements with Respect to the Modified Mercalli Intensity," *Earthquake Notes* 47(1), 9-21 (1976).
8. R. K. McGuire, "The Use of Intensity Data in Seismic Hazard Analysis," *Proc. 6th World Conf. on Earthquake Eng.*, New Delhi, 1977, pp. 709-14.
9. O. W. Nuttli, R. Rodriguez, and R. B. Herrmann, *Strong Ground Motion Studies for South Carolina Earthquakes*, NUREG/CR-3755, Lawrence Livermore National Laboratory, April 1984.
10. K. W. Campbell, *An Empirical Assessment of Near-Source Strong Motion for 6.6 m_b (7.5 M_s) Earthquake in the Eastern United States*, NUREG/CR-3839, Lawrence Livermore National Laboratory, June 1984.

Appendix F

RESPONSE SPECTRA

Earthquake vibratory ground motions are characterized for design by their amplitude, frequency content, and duration. The duration and frequency of *recorded* ground motion can be determined directly from the acceleration record. The frequency content of acceleration records can be observed qualitatively by comparing different records plotted to the same scale, but the frequency content cannot be defined quantitatively in this manner. Dynamic seismic analyses of most nuclear plant structures can be performed using design response spectra as the dynamic input into the analysis. The analysis of special structures, piping, and equipment housed in structures in most cases requires that they be analyzed using acceleration time histories. Design acceleration time histories are usually artificial time histories constructed to yield response spectra that are comparable to the design response spectra.

Response spectra may be prepared that display peak response acceleration, velocity, or displacement in separate plots or all can be displayed on a tripartite plot. The tripartite plot is universally used for defining design criteria because it provides much more useful information in one plot (see Fig. F.1).

The response spectrum for a particular earthquake acceleration record will normally show a series of peaks and valleys at different frequencies because each record results from a different specific set of physical conditions unique to a specific earthquake and a specific site (the source mechanism of the earthquake, the transmission path of the seismic waves, and the local site conditions). For a particular set of conditions pertaining only to a specific earthquake and a specific site, certain frequencies of the response spectrum will be amplified and others will be suppressed or attenuated.

No two historical earthquake records ever yield the same response spectra. However, general spectral shapes may be nearly the same for certain nearly alike conditions. Since many factors that influence response spectra vary from one earthquake to another and from one site to

Fig. F.1. Scales used on a tripartite plot. Axes are all logarithmic. Lines of constant velocity are horizontal. Lines of constant displacement and acceleration have slopes of -1 and $+1$, respectively.

another, design response spectra are based on prediction procedures derived from statistical analyses of response spectra computed from several earthquake records (see Fig. F.2). Design response spectra consist of either smooth curves or a series of straight lines and do not have peaks and valleys that are characteristic of a spectrum derived from a single record.

Response spectra correlations have been derived by many researchers and are discussed in the open literature.¹⁻⁶ However, we are only interested in three "standard" response spectra shapes: (1) the spectra recommended by the Nuclear Regulatory Commission for the seismic design

Fig. F.2. Median and median plus one standard distribution for normal distribution of 33 records for horizontal acceleration between 0.05 g and 0.12 g at 2% damping.

of nuclear power plants,⁷ (2) the spectra recommended by the applied technology council for the seismic design of buildings,³ and (3) the spectra recommended by Newmark and Hall for the design of all types of buildings though originally developed for the design of nuclear power plants.⁴ These spectra comprise those commonly used in design today.

The procedures for developing design response spectra for nuclear power plants are provided in *Regulatory Guide 1.60* (Ref. 7). The basis for these procedures is summarized in a paper authored by Newmark, Blume, and Kapur.⁸ These spectra are based on statistical analyses of response spectra of strong-motion earthquakes as described in Ref. 8. These spectra — considered to be approximately $(M + \sigma)$ spectra — were selected to represent an 84th percentile spectra when anchored to a median of peak ground acceleration. The procedures are applicable to rock or soil sites

and all frequencies of interest, but do not apply to sites that are relatively close to the epicenter of an expected earthquake or to sites that are underlain by poor soil conditions. The *Regulatory Guide* provides procedures for developing both horizontal and vertical response spectra. The procedure for defining horizontal response spectra is set forth in Fig. F.3. The maximum values of peak ground acceleration and displacement specified for the "standard earthquake" are 91.4 cm of peak ground displacement for a peak horizontal ground acceleration of 1.0 g.

Referring to Fig. F.3, each design spectrum is defined by a series of five straight lines, which intersect at four control frequencies indicated by A, B, C, and D. The peak ground acceleration is estimated first, based on the results of the geological, seismological, and probabilistic investigation. The peak ground displacement is estimated by proportion from the specified relationship of 91.4 of displacement for a peak horizontal ground acceleration of 1.0 g. The amplitude response for the control points for the construction of spectra for different levels of critical damping is estimated by multiplying the peak ground acceleration and displacement by the appropriate amplification factors given in Fig. F.3(a). Response spectra for a site having a predicated peak ground acceleration of 0.1 g are provided in Fig. F.3(b).

The *Guide* provides procedures for defining vertical response spectra by having $2/3$ of the response of the horizontal spectra at frequencies <0.25 Hz and vertical response that is equal to the horizontal response for frequencies >3.5 Hz, while the ratio varies between $2/3$ and 1 for frequencies between 0.25 and 3.5. For frequencies higher than 33 Hz the response spectra follows the peak ground acceleration line.

The response spectra recommended by the Applied Technology Council (ATC) (Ref. 3) have a spectra representative of different soil conditions selected on the basis of a statistical study of spectra developed on such soils close to the seismic source zone in past earthquakes. The curves were simplified to a family of three by combining the spectra for rock and stiff soil conditions leading to the normalized spectra shown in Fig. F.4. These curves represent smoothed spectra for the following three soil conditions.

DAMPING, % CRITICAL	AMPLIFICATION FACTORS FOR CONTROL POINTS			
	ACCELERATION			DISPLACEMENT ^a D(0.25 Hz)
	A(33 Hz) ^a	B(9 Hz)	C(2.5 Hz)	
0.5	1.0	4.96	5.95	3.20
2.0	1.0	3.54	4.25	2.50
5.0	1.0	2.61	3.13	2.05
7.0	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

^aMAXIMUM GROUND DISPLACEMENT IS TAKEN PROPORTIONAL TO THE DESIGN MAXIMUM ACCELERATION, AND IS 3.6 in. FOR A DESIGN ACCELERATION OF 0.1 G.

(a)

Fig. F.3. Regulatory Guide 1.60 design response spectra for horizontal ground motion.

Fig. F.4. Normalized ATC response spectra recommended for use in building design.

Soil profile type S1: Rock of any characteristic, either shale-like or crystalline in nature (such material may be characterized by a shear wave velocity $>76,200$ cm/s); or stiff soil conditions where the soil depth is <6096 cm, and the soil types overlying rock are stable deposits of sands, gravels, or stiffer clays.

Soil profile type S2: Deep cohesionless or stiff clay soil conditions, including sites where the soil depth exceeds 6096 cm and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

Soil profile type S3: Soft-to-medium stiff clays and sands, characterized by 914.4 cm or more of soft- to medium-stiff clay with or without intervening layers of sand or other cohesionless soils.

The recommended ground motion spectra are obtained by multiplying the normalized spectra shown in Fig. F.4 by values of effective peak ground acceleration (EPA) and the correction factor 0.8 for soil type S3. The resulting ground motion spectra for 0.4 g EPA are shown in Fig. F.5.

Fig. F.5. ATC ground motion spectra for 0.4-g effective peak acceleration.

In the ATC report³ contour maps of effective peak acceleration and velocity are given for different regions of the United States. However, it is felt that EPA, as used in this report, is equivalent to peak ground acceleration since the spectra shapes are similar to those developed for peak ground acceleration. For relatively large distances, ATC recommends that the velocity portion of the spectra (Fig. F.5) be multiplied by the ratio of effective velocity to effective acceleration and the remainder of the spectra extended to maintain the same overall shape. This takes into account the change in the spectra that has been observed to occur at large distances. The spectra shapes remain independent of earthquake magnitude. Spectra for vertical motions are determined by multiplying the horizontal spectra by a factor of 0.67.

The response spectra procedure recommended by Newmark and Hall for seismic design of buildings is provided in a monograph⁴ published by the Earthquake Engineering Research Institute. This procedure recommends that appropriate regions of the spectra be scaled by peak acceleration, peak velocity, and peak displacement. This enables the spectra to vary with magnitude, distance, and site conditions in accordance with the variation in these peak ground motion variables. The procedure gives amplification parameters for both median and one sigma or 84th percentile spectra. Figure F.6 presents these factors for a series of damping values and a sample spectra for horizontal motion.

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DAMPING, % CRITICAL	ONE SIGMA (84.1%)			MEDIAN (50%)		
	A	V	D	A	V	D
0.5	5.10	3.84	3.04	3.68	2.59	2.01
1.0	4.38	3.38	2.73	3.21	2.31	1.82
2.0	3.66	2.92	2.42	2.74	2.03	1.63
3.0	3.24	2.64	2.24	2.46	1.86	1.52
5.0	2.71	2.30	2.01	2.12	1.65	1.39
7.0	2.36	2.08	1.85	1.89	1.51	1.29
10.0	1.99	1.84	1.69	1.64	1.37	1.20
20.0	1.26	1.37	1.38	1.17	1.08	1.01

(a)

(b)

Fig. F.6. Newmark and Hall design response spectra for horizontal motion. (a) Spectra amplification factors for horizontal response, and (b) spectra for site having 0.5-g maximum acceleration and 5% damping.

In determining the ground motions, it is recommended that, lacking other information, (1) values of peak velocity be estimated from values of acceleration, (2) for competent soil conditions a velocity/acceleration ratio of 121.9 cm/s/g be used, and (3) for rock a velocity/acceleration ratio of 91.4 cm/s/g be used.⁴ Also, an acceleration-distance/velocity squared ratio equal to 6.0 is recommended to ensure that the spectra represent a frequency band adequate to accommodate a possible range of earthquakes.

For the above described procedures, the design spectra for earthquake motions can be drawn as shown in Fig. F.7. The symbols D , V , A , and A_0 refer, respectively, to peak displacement, peak velocity, peak acceleration, and maximum effective acceleration. For low frequencies

Fig. F.7. Typical spectra for engineering analysis.

to about 0.3 Hz, displacements are nearly constant. For frequencies of 0.3 to ~2 Hz, velocity is nearly constant. For frequencies between ~2 to ~8 Hz, the acceleration is nearly constant. There is a transition region between 8 and 33 Hz between the amplified peak acceleration and the maximum effective acceleration. To estimate the vertical response spectra use a scale factor of 2/3 to ratio the horizontal spectra to the vertical spectra.

References

1. G. A. Young, *Definition of Design Earthquake Vibratory Ground Motion Recommended Guidelines*, SAN-1011-124, Agbabian Associates, March 1980.
2. W. W. Hays, *Procedures for Estimating Earthquake Ground Motions*, Geological Survey Professional Paper 1114, United States Government Printing Office, Washington, D.C., 1980.
3. *Tentative Provisions for the Development of Seismic Regulations for Building*, National Bureau of Standards Special Publication 510, Applied Technology Council Report, ATC-3-06, June 1978.
4. N. M. Newmark and W. J. Hall, *Earthquake Spectra and Design*, Earthquake Engineering Research Institute, Berkeley, Calif., 1982.
5. D. E. Hudson, *Reading and Interpreting Strong Motion Accelerograms*, Earthquake Engineering Research Institute, Berkeley, Calif., 1979.
6. D. P. Reddy, ed., *Seismic Design Technology for Breeder Reactor Structures, Vol. 1: Special Topics in Earthquake Ground Motion*, DOE/SF/01011-T25 (Vol. 1), 1983.
7. *U.S. Atomic Energy Commission Regulatory Guide 1.60*, Directorate of Regulatory Standards, 1973.
8. N. M. Newmark, J. A. Blume, and K. K. Kapur, "Seismic Design Spectra for Nuclear Power Plants," *ASCE J. Pow. Div.* 99(P02) (November 1973).

Appendix G

SOURCE PARAMETERS

In the early 1960s, the propagation of long-period surface waves was already well understood. Thus, the study of the slip function was begun from the low-frequency end of the seismic spectrum in the period range longer than ~20 s. Through the low-frequency window the details of the earthquake rupture could not be seen, but Aki¹ was able to determine a new earthquake source parameter called "seismic moment" M_0 with an unprecedented high accuracy for a source parameter. The seismic moment is the moment of an equivalent point double couple and is equal to the final slip integrated over the whole area of the fault plane multiplied by the medium rigidity

$$M_0 = \mu \bar{D} A, \quad (G.1)$$

where μ is rigidity modulus, $\bar{D}$ is average fault displacement, and A is the fault rupture area. The other major source parameters are:²

- L = fault length,
- W = fault width,
- v = rupture velocity,
- T = rise time,
- $\Delta\sigma$ = stress drop,
- f = corner frequency.

Researchers studying source parameters use theoretical earthquake models such as the Aki, Haskell, Brune, and Savage models³ to develop and calculate the parameters.

Nuttli⁴ used the Savage fault dislocation model^{2,3} to obtain estimates of the average values of fault displacement, source rise time, rupture velocity, fault rupture length and width, and average stress drop for a given seismic moment of midplate earthquakes. Midplate earthquakes, which are defined as having their epicenters at least 500 km from (tectonic) plate margins, represent a small portion of the total global seismicity. However, since they occur within continental interiors, they

are characterized by large damage areas. Nuttli developed a proposed spectrum for far-field displacement observed at a fixed distance from earthquakes with different body wave m_b or surface wave M_s magnitudes. Figure G.1 shows the proposed spectra and/or scaling relations for midplate earthquake. In general, the idealized spectra consist of three straight-line segments of slope zero, one, and two. The period corresponding to the intersection of portions of slope one and two is called T_2 (corner frequency f_2) and, correspondingly, T_1 (corner frequency f_1) is the period of the intersection of curves of slope zero and one. For

Fig. G.1. Proposed far-field spectra for midplate earthquakes.

larger earthquakes, the portion of the spectrum having unit slope is needed to satisfy the empirical m_b , M_s , and M_0 data. Spectra containing only one corner period T cannot be constructed to satisfy the observational magnitude and moment data. The corner period T_2 is numerically equal to the source rise time and is related to the fault width W and rupture velocity v by

$$W = 2.3 v T_2 / \pi . \quad (G.2)$$

The relation between fault length L and corner period T depends on the angle between the plane of the fault surface and the ray path (wave radiation) at the fault surface. Savage in his model³ gives T_1 as a function of the ratio of rupture velocity to wave velocity. If the rupture velocity v is taken to be 0.9β , where β is the shear velocity, Savage gives

$$L = 3.57 \beta T_1 / \pi . \quad (G.3)$$

For a rectangular dislocation model,³ the average stress drop $\Delta\sigma$ in terms of seismic moment and fault rupture dimensions is

$$\Delta\sigma = 7 M_0 / 16 (LW/\pi)^{3/2} . \quad (G.4)$$

As a consequence of the scaling relations shown in Fig. G.1, the relations between m_b and $\log M_0$ for midplate earthquakes are

$$\begin{aligned} \log M_0 &= 1.0 m_b + 17.7 \text{ for } m_b < 4.5 , \\ \log M_0 &= 2.0 m_b + 13.2 \text{ for } m_b > 4.5 , \end{aligned} \quad (G.5)$$

where M_0 is in dyne-centimeters. The spectral scaling relation leads to the equation between M_s and M_0 as

$$\log M_0 = 1.0 M_s + 18.85 . \quad (G.6)$$

In addition to the m_b , M_s , and M_0 interrelations, the spectral scaling relations are influenced by the dependence on seismic moment of the corner period T (the period corresponding to the intersection of the long-period portion of the spectrum of slope zero and the short-period portion

of the spectrum of slope two). The equation relating T to M_0 is

$$\log M_0 = 4.0 \log T + 22.2 . \quad (G.7)$$

Table G.1 gives average values of the source parameters for midplate earthquakes as obtained by applying Eqs. (G.1)–(G.7) to the spectral data given in Fig. G.1. The fault rupture length and width estimates do not depend strongly on the assumed rupture velocity. For example, decreasing v from 0.98 to 0.88 causes W to decrease by ~10% and L to increase by 30%. For $T = T_1 = T_2$ ($m_b < 4.5$) the equation from Aki and Richards²

$$\sqrt{LW} = \frac{\sqrt{14.8} \beta T}{2\pi} \quad (G.8)$$

was used to calculate L and W , which are assumed to be equal.

Table G.1. Average source parameters for midplate earthquakes^a

m_0	M_s	$\log M_0$ (dyne-cm)	T_1 (s)	L (km)	T_2 (s)	W (km)	$\Delta\sigma$ (bars)	D (m)
3.0	1.85	20.7	0.39	0.8	0.39	0.8	2.4	0.002
3.5	2.35	21.2	0.53	1.1	0.53	1.1	2.6	0.004
4.0	2.85	21.7	0.73	1.6	0.73	1.6	3.2	0.006
4.5	3.35	22.2	1.00	2.1	1.00	2.1	4.2	0.011
5.0	4.35	23.2	1.87	3.8	1.67	3.8	7.0	0.033
5.5	5.35	24.2	3.50	7.0	2.78	6.4	13	0.11
6.0	6.35	25.2	6.53	13	4.63	11	23	0.34
6.5	7.35	26.2	12.2	24	7.71	18	43	1.1
7.0	8.32	27.2	22.8	45	12.8	29	82	3.7
7.2	8.53	27.6	29.3	58	15.7	36	102	5.8
7.4	8.87	28.0	37.7	75	19.3	44	129	9.2
7.5	9.00	28.2	42.7	85	21.4	49	143	11.5

^aAssumes $\beta = 3.5$ km/s, $v = 0.9$, $\beta = 3.15$ km/s, and $\mu = 3.3 \times 10^{11}$ dyne/cm².

The relations between M_0 and the fault dimensions, L and W , can be described by the equations

$$\begin{aligned} \log M_0 &= 3.65 \log L + 21.0 \text{ for } M_0 > 1.5 \times 10^{23} \text{ dyne-cm} , \\ \log M_0 &= 4.55 \log W + 20.5 , \\ \log M_0 &= 3.65 \log L \text{ (or } W) + 21.0 \text{ for } M_0 < 1.5 \times 10^{23} \text{ dyne-cm} , \end{aligned} \quad (G.9)$$

where L and W are in kilometers. The average stress drop $\Delta\sigma$ and the average fault displacement are given by the relations

$$\log M_0 = 3.82 \log \Delta\sigma + 19.95 \text{ for } M_0 > 1.5 \times 10^{23} \text{ dyne-cm}, \quad (G.10)$$

$$\log M_0 = 2.02 \log D + 22.0, \quad (G.11)$$

where $\Delta\sigma$ and D are in bars and centimeters, respectively. The study done by Nuttli shows that midplate earthquakes differ from plate-margin events in the following ways:

1. seismic moment is proportional to the fourth power of the corner period, T ;
2. stress drop increases with seismic moment rather than remaining constant; and
3. the corner periods of large midplate earthquakes are smaller than plate-margin earthquakes, and the fault rupture dimensions are smaller.

This study shows that large magnitude earthquakes can occur with relatively small rupture lengths. This affects hazard calculations because it indicates that short faults have the potential for producing large earthquakes and large ground motions. The relations developed in Nuttli's study can be used to calculate response spectra for fault systems in the eastern United States even though worldwide midplate earthquake data were used. An excellent discussion of the differences between midplate and plate margin earthquakes or eastern and western United States earthquakes is given in Ref. 5.

The relationship between seismic source parameters and magnitude has been studied by many researchers. Some of the relations developed are discussed below.

Thatcher and Hanks⁶ developed an empirical relationship between magnitude M_L and seismic moment M_0

$$M_L = 2/3 \log M_0 - 10.7 \text{ for } M_L < 7. \quad (G.12)$$

This relationship was developed using near-source western data but should

prove useful as a check or reference point for the eastern regions. Bakun and Lingh⁷ developed an empirical relationship, also based on western data, between M_L and M_0

$$M_L = 0.83 \log M_0 - 14.17 \text{ for } 17 < \log M_0 < 25 . \quad (G.13)$$

For the complete United States, a relation developed by Mark⁸ relates average fault rupture length L in meters to magnitude M (M_b if $M > 6.75$ or M_L if $M < 6.75$) and is given by

$$\log (L) = 1.915 + 0.389 M . \quad (G.14)$$

Reference 3 lists many empirical relations between source parameters and magnitude. The equations given here, along with those listed in Ref. 3, can be used to give an estimate of earthquake size or magnitude based on geological studies to measure the source parameters.

References

1. K. Aki, "Earthquake Source Mechanism," *Earthquake Source Modeling, Ground Motion and Structural Response*, ASME AMD-Vol. 60, June 1984.
2. K. Aki and P. G. Richards, *Quantitative Seismology, Theory and Methods*, Vol. II, pp. 799-849, W. H. Freeman and Company, San Francisco, 1980.
3. K. Kasahara, *Earthquake Mechanics*, Cambridge University Press, New York, 1981.
4. O. W. Nuttli, "Average Source-Parameter Relations for Mid-Plate Earthquakes," *Bull. Seismol. Soc. Am.* 73(2), 519-35 (April 1983).
5. O. W. Nuttli, "Similarities and Differences Between Western and Eastern United States Earthquakes, and Their Consequences For Earthquake Engineering," *Proceedings of Earthquakes and Earthquake Engineering. The Eastern United States*, September 14-16, 1981, Vol. 1, Knoxville, Tenn.
6. A. F. Shakal and D. L. Bernreuter, *Empirical Analysis of Near-Source Ground Motion*, NUREG/CR-2095, Lawrence Livermore Laboratory, September 1981.

7. M. E. O'Neill, "Source Dimensions and Stress Drops of Small Earthquakes Near Parkfield, California," *Bull. Seismol. Soc. Am.* 74(1), 27-40 (February 1984).
8. S. T. Algermissen et al., *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States*, United States Department of the Interior, Geological Survey, Open-File Report 82-1033, 1982.

Appendix H

POISSON PROCESSES IN EARTHQUAKE FORECASTING

Earthquake events are regarded as being random in nature because of uncertainties regarding the underlying processes that cause earthquakes. As a result, they are often forecast using Poisson stochastic processes, a well-known approach for predicting the occurrence of random events. For earthquake events to be considered as forming a Poisson process, three conditions must be satisfied:

1. spatial independence,
2. temporal independence, and
3. negligible probability that two or more seismic events will take place at the same time and the same location.

The first two conditions imply that the occurrence or absence of a seismic event at one site does not affect the occurrence or absence of seismic events at other sites or times (i.e., the process has no spatial or temporal memory). The third condition implies that, over a short time interval, no more than one seismic event can occur inside a small geographical region. There are more complex statistical models than the Poisson model, but the ease of use has led to Poisson's popularity among earthquake engineers. The other more complex models introduce parameters that cannot be reasonably determined from seismic history.

Given the mean occurrence rate N (earthquakes per unit of time) of all earthquakes from a given source, the probability of occurrence of n earthquakes at a magnitude or epicentral intensity value during a time interval of duration or exposure time t is

$$P(n,t) = e^{-Nt} (Nt)^n / n! . \quad (H.1)$$

In particular, for no events $n = 0$, Eq. (H.1) becomes

$$P(0,t) = e^{-Nt} , \quad (H.2)$$

and for one event $n = 1$, Eq. (H.1) becomes

$$P(1,t) = e^{-Nt} (Nt) . \quad (H.3)$$

Then Eq. (H.2) gives the probability of nonoccurrence of an earthquake, and the probability of occurrence of a given site intensity or magnitude within t years is

$$P = 1 - e^{-Nt} . \quad (H.4)$$

The return period for an earthquake of this level can be computed as

$$T = \frac{1}{N} \quad (H.5)$$

and is related to the probability of occurrence P through the expression

$$P = 1 - e^{-t/T} , \quad (H.6)$$

and the probability of nonoccurrence as

$$P(0,t) = e^{-t/T} . \quad (H.7)$$

It may be useful to point out that using Eq. (H.7) and setting the exposure time equal to the average return period, Eq. (H.7) becomes

$$P(0,t) = e^{-1} = 0.37 .$$

Thus, the earthquake event with a return period $T = t$ years has a probability of [see Eq. (H.6)]

$$P = 1 - 0.37 = 0.63 \text{ or } 63\%$$

of being exceeded in t years. This simple calculation shows that events with a particular return period have a 63% probability of being exceeded during an exposure time equal to the return period. Because an event with a return period of T years is often incorrectly associated with zero probability of exceedence in less than T years, it is preferable to explicitly state the probability of exceedence and exposure time with a particular event. The Poisson statistical model is used in all the probabilistic procedures in this report, and this simple discussion of the statistical model should prove useful when reading the other appendices on statistics.

Appendix I

EARTHQUAKE RECURRENCE RELATIONSHIPS

This section discusses procedures for estimating return intervals of earthquakes. In addition, probabilistic concepts relevant to earthquakes will be discussed.

The most commonly used approach for estimating the recurrence of earthquakes was originally proposed by Gutenberg and Richter.¹ In this procedure, curves relating earthquake magnitude or epicentral intensity are plotted vs the frequency of occurrence (or inverse of the return period). If this is done separately for different areas and the results are normalized to account for differences in the sizes of areas, the levels of seismic activity in each of the areas can be compared. This technique has the advantage of averaging many events and reducing the effects of isolated nontypical events.

The form of the recurrence relation in terms of earthquake magnitude or intensity is

$$\log N = a - bM ,$$

or

$$\log N = a - bI_0 , \tag{I.1}$$

in which N refers to the frequency of occurrence (earthquakes per year), M refers to magnitude, I_0 epicentral intensity, and a and b are constants determined from a tabulation and statistical assessment of the earthquake data. Typically, the equation is plotted as a straight line on semilog paper; this plot is termed the recurrence curve for the region under investigation.

Equation (I.1) represents the most widely used and accepted form for representing the frequency of occurrence or number of earthquakes per year. Other forms of the recurrence relationships have been developed and proposed by many investigators in the past, but the ease of using Eq. (I.1) form outweighs using a more accurate form. Tables I.1 and I.2 list recurrence relations for the eastern United States using magnitude or epicentral intensity. The variations in the different regions can be

Table I.1. Table of recurrence relations using epicentral intensity

$$(\log N = a - bI_0)$$

Region	Developer	Reference	a	b	Interval
Northeastern United States and southeastern Canada	Chiburis	2	2.755	0.417	III < I_0 < VII
Portsmouth, Ohio	J. C. Wiggins Co.	3	-0.164	1.560 ^a	VII < I_0 < VIII
New York	Mitronovas	4	3.34	0.6	
Ramapo Fault System (New York and New Jersey)	Fischer	5	5.06	0.73	
Southeastern United States	Bollinger	6	1.65	0.54	
Southern Appalachian	Bollinger	6	3.01	0.59	
East Coast (except Florida)	Algermissen	7	2.72	0.57	
Mississippi and St. Lawrence Valleys	Algermissen	7	3.02	0.58	
Oklahoma, North Texas	Algermissen	7	2.71	0.5	
Nebraska, Kansas, Oklahoma	Algermissen	7	2.10	0.55	
		7	1.99	0.49	

^a($I_0 - 7$).

Table I.2. Table of recurrence relations using magnitude

$$(\log N = a - bM)$$

Region	Developer	Reference	a	b	Interval
Northeastern United States and southeastern Canada	Chiburis	2	3.45	0.695	$2.8 < M < 5.2$
New Madrid	Johnson	8	-0.164	2.601^a	$5.2 < M < 5.8$
New Madrid	Nuttli and Brill	8	3.27	0.89^b	
Central Mississippi Valley	Nuttli	6	3.28	0.91^b	
Upper Mississippi Embayment	Nuttli	6	3.50	0.92^b	
Southern United States	Bollinger	6	4.34	1.09^b	
Southern Appalachian	Bollinger	6	3.90	0.89	
			3.58	0.86	

$a_M = 5.2$.

$b_M = m_b$ body wave magnitude.

seen by the variations in the a and b constants. Although the b constants (slope of line) listed in both tables are very similar, the value of a, which is related to the mean minimum annual activity rate, varies greatly from region to region. The parameter b defines the relative frequency of occurrence of various magnitude or epicentral intensity. The values of b for regions of the eastern United States have been estimated by several investigators. The recurrence relations are of great importance when doing probabilistic estimates of ground motion. Appendix B lists values of b for seismic source zones throughout the United States.

It should be pointed out that for large magnitudes or intensities almost no data exist on the recurrence rates in the eastern United States. Extrapolation of the present relations to high values involves great uncertainty since the relations are based on smaller and much more frequent earthquakes.

References

1. B. Gutenberg and C. F. Richter, *Seismicity of the Earth and Related Phenomena*, Hafner Publishing Co., New York, 1954.
2. E. F. Chiburis, *Seismicity, Recurrence Rates, and Regionalization of the Northeastern United States and Adjacent Southeastern Canada*, NUREG/CR-2309, Western Observatory, Boston College, September 1981.
3. *Seismic Criteria for the Design, Analysis, and Test of the Gas Centrifuge at Portsmouth, Ohio*, Technical Report No. 80-1374-6, May 1981.
4. W. Mitronovas, "Temporal and Spatial Variations in Seismicity Within New York State and Eastern United States," *Proceedings of Earthquake and Earthquake Engineering: The Eastern United States*, Vol. 1, pp. 143-60, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich., 1981.
5. J. A. Fischer, "Capability of the Ramapo Fault System," *Proceedings of Earthquake and Earthquake Engineering: The Eastern United States*, Vol. 1, pp. 143-60, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich., 1981.
6. G. A. Young, *Problem Areas in the Application of Seismic Hazard Analysis Procedures*, Agbabian Associates, SAN/1011-101, June 30, 1976.

7. W. W. Hays, *Procedures for Estimating Earthquake Ground Motions*, Geological Survey Professional Paper 1114, United States Government Printing Office, 1980.
8. A. C. Johnson, "On the Use of the Frequency-Magnitude Relation in Earthquake Risk Assessment," *Proceedings of Earthquakes and Earthquake Engineering: The Eastern United States*, Vol. 1, pp. 161-78, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich., 1981.

Appendix J

SEISMIC PROBABILISTIC ANALYSIS

Seismic probabilistic analyses in the United States are generally presented in one of two forms; probabilistic ground motion maps and/or annual exceedence probability vs ground motion parameter curves. Both are based on probabilistic analyses of known seismic events and recurrence data of earthquakes. Seismic probability maps are discussed first.

The concept of probability mapping used here assumes that earthquakes are exponentially distributed with regard to magnitude and randomly distributed with regard to time. The exponential magnitude distribution is based on empirical observation. The distribution of earthquakes in time is assumed to be Poissonian. The assumption of a Poisson process for earthquakes in time is consistent with historical earthquake occurrences. Large events closely approximate a Poisson process, whereas small events may depart significantly from a Poisson process. The ground motion from small earthquake events is of very little interest in engineering applications, and, therefore, the Poisson assumption gives a useful and simple model (see Poisson Processes, Appendix H).

Spatially, the seismicity is modeled by grouping it into discrete areas termed seismic source zones. The general requirements for a seismic source zone are that it must have seismicity and it must be a reasonable seismotectonic or seismogenic structure or zone. A seismotectonic structure or zone is defined as a geologic feature or group of features throughout which the type of deformation and tectonic setting are similar, and a relationship between this deformation and historic earthquake activity can be inferred.

The above discussion outlines the concept of the National Probabilistic Seismic Maps.¹ The development of these probabilistic ground motion maps used the previously discussed concept and involved three principal steps: (1) delineation of seismic source areas, (2) analysis of the statistical characteristics of historical earthquakes in each seismic source area, and (3) calculation and mapping of the cumulative probability of nonoccurrence $F_{\max}$ of ground motion [see Eq. (H.7) in Poisson

Processes, Appendix H] for some time t . The probability is

$$F_{\max} = e^{-t/T} . \quad (J.1)$$

For each source zone, attenuation relations, recurrence relations, and seismicity of the zone are used to statistically estimate the ground motion in the zone. The recurrence relation is of the form

$$\log N = a - bM , \quad (J.2)$$

where N is the number of earthquakes in a given magnitude range per unit time, and M is the magnitude of the earthquakes of interest. Note that each source zone has a set of constants a and b . The seismicity of each zone is based on historical seismicity together with an evaluation of available geological evidence related to earthquake activity.

In the development of the national maps, workshops were held around the United States to develop the information necessary to make up the maps. The workshop participants took the following approaches in outlining the seismotectonics in a region: (1) seismotectonic zoning on individual faults or the area extent of faulting that shows late quaternary or Holocene displacements or historical seismicity, (2) zoning primarily on regional structural conditions, and (3) zoning on spatial distribution of seismicity in the absence of any aspects of (1) and (2) above. The zones developed by the workshop participants provided an invaluable source of information for the development of the zones used to prepare the probabilistic maps. The development of the national earthquake probability maps demonstrates that interdisciplinary efforts with the objective of integrating geological and geophysical data and interpretations of data to produce improved estimates of expected ground motion are possible. The new maps represent an improvement in the application of probabilistic ground motion to earthquake-resistant design for two principal reasons. First, the development of both acceleration and velocity maps makes possible the estimation of a response spectrum at a site and comparison of response spectra at any number of sites under consideration. The use of different attenuation relations in the central, eastern, and western United States takes into account the difference in

attenuation in these parts of the country for design purposes. Second, the change in earthquake probability with exposure time can be estimated at any site because ground motion estimates for three exposure times — 10, 50, and 250 years — are presented. A more complete discussion of the development of these maps is given in Ref. 1.

The probability maps for horizontal acceleration are given in Figs. J.1–J.3, and for horizontal velocity in Figs. J.4–J.6. As more research is done on geology and seismicity, regional maps in greater detail will be developed for use by design engineers. Table J.1 lists some important statistical parameters for the seismic probability maps of 90% probability of not being exceeded, which will be very useful when using the maps.

Table J.1. Some important statistical parameters of the hazard maps

Exposure ^a time (years)	Average ^b return rate (years)
10	94.9
50	474.6
250	2372.8

^aThe ground motion values have a probability of 10% being exceeded in the exposure time.

^bThe ground motion values have a probability of 63% of being exceeded in the average return period.

Probability curves are developed by breaking the region around the site of interest into a number of source zones. The curve ordinate, the probability P of an event occurring in a given number of years, is given by

$$P(GM) = \iint P(M, R, GM) f_m(M) dM dR, \quad (J.3)$$

Fig. J.1. Preliminary map of horizontal acceleration (expressed as percent of gravity) in rock with 90% probability of not being exceeded in 10 years. Source: Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

Fig. J.2. Preliminary map of horizontal acceleration (expressed as percent of gravity) in rock with 90% probability of not being exceeded in 50 years. Source: Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

Fig. J.3. Preliminary map of horizontal acceleration (expressed as percent of gravity) in rock with 90% probability of not being exceeded in 250 years. Sources: Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

Fig. J.4. Preliminary map of horizontal velocity (expressed in centimeters per second) in rock with 90% probability of not being exceeded in 10 years. *Source:* Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

Fig. J.5. Preliminary map of horizontal velocity (expressed in centimeters per second) in rock with 90% probability of not being exceeded in 50 years. Source: Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

Fig. J.6. Preliminary map of horizontal velocity (expressed in centimeters per second) in rock with 90% probability of not being exceeded in 250 years. Source: Dept. of the Interior, U.S. Geological Society, Open-File Report No. 82-1033.

where M is the magnitude of the earthquake event, and R is the distance to the source. The function F_m is the cumulative distribution function of magnitude for each event and is given by

$$F_m(M) = \frac{1 - e^{-\beta(M - M_0)}}{1 - e^{-\beta(M_1 - M_0)}} \quad \text{for } M_0 < M < M_1, \quad (J.4)$$

where $\beta = b \ln 10$, M_0 = minimum magnitude of interest, and M_1 is maximum possible. This function is based on the recurrence relation

$$\log N = a - bM,$$

where a and b are constants characteristic of the source area being examined and N is the number of earthquakes having a magnitude greater than M . The probability density function f_m , based on Eq. (J.4), is

$$f_m(M) = \frac{\beta e^{-\beta(M - M_0)}}{1 - e^{-\beta(M_1 - M_0)}} \quad M_0 < M < M_1. \quad (J.5)$$

The probability function $P(M, R, GM)$ is based on the probability and/or statistics of the attenuation relations or data used for attenuation between the sources and sites of interest. The attenuation relations can have as variables: magnitude, distance, focal depth, and ground motion parameters, all of which can have probabilistic or statistical distributions. Therefore, the exact mathematical form of $P(M, R, GM)$ is very complex.

Reference 2 gives a derivation of Eq. (J.3) and a description of a computer code written to integrate Eq. (J.3). The equation is used to calculate ground motion parameters, magnitudes, or intensities for corresponding probabilities of exceedence. The results of such calculations are used to plot annual exceedence probability vs ground motion parameter,^{2,3} as shown in Fig. J.7. Such curves, along with the seismic probability maps, can be very useful to help set the maximum ground motion parameters for a design.

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Fig. J.7. Example of the relationship between probability of exceedence and peak ground acceleration.

References

1. S. T. Algermissen et al., *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States*, United States Department of the Interior, Geological Survey, Open-File Report 82-1033 (1982).
2. R. K. McGuire, *FORTTRAN Computer Code for Seismic Risk Analysis*, United States Department of the Interior, Geological Survey, Open-File Report 76-67 (1976).
3. D. L. Bernreuter, D. H. Chung, and C. P. Mortgat, *Seismic Safety Margin Research Program, Phase I Final Report - Development of Seismic Input (Project II)*, NUREG/CR-2015, Lawrence Livermore National Laboratory, Vol. 3 (January 1983).

Appendix K

ATTENUATION

Attenuation describes the energy loss suffered by seismic waves as they propagate outward from the source region. In general, attenuation varies with frequency. Three different physical processes contribute to the overall attenuation: (1) geometrical spreading, (2) absorption, and (3) scattering. Geometrical spreading occurs because the total energy present in the seismic waves cannot exceed that which was released during the motion of the fault. Yet, this energy is spread over an area that increases approximately in proportion to the square of epicentral distance, or equivalently, travel time. Thus, the amplitude of the waves, which depends on the square root of the energy per unit area in the wave front, decreases approximately in inverse proportion to epicentral distance.

Absorption describes the conversion of part of the seismic energy into heat by internal friction processes in the rocks through which the wave passes. Absorption is a complex physical process, which has been theoretically described¹⁻¹⁰ and measured in the laboratory, although such measurements are often made at ultrasonic (~1-MHz) frequencies.¹⁰

Scattering of seismic waves occurs because the earth is inhomogeneous and contains geologic structures whose dimensions approximate the wavelength of the waves generated by earthquakes. Scattering is a geometrical effect in the sense that energy is not converted into heat, but it instead acts to reduce the amplitude of the primary seismic waves and increases the observed duration of the earthquake as part of the energy traverses complex and lengthy ray paths. Scattering incorporates a large variety of effects, including reflection and refraction by thin rock layers,¹¹ and diffraction by small and large irregularities in the subsurface structure.¹²⁻¹⁵

Attenuation is poorly known for the eastern United States, partly because the process is complex, and partly because little data are available. For engineering purposes, it is important to know the rate at which seismic waves at frequencies higher than 1 Hz attenuate. However,

much of the available data from earthquakes are applicable to lower frequencies.

The existing attenuation data are of two types: (1) isoseismal maps, which depict Modified Mercalli Intensities for historical earthquakes, and (2) seismographic data recorded by instruments at various distances from the earthquake hypocenter.

The analysis of isoseismal data yields equations that describe the reduction of Modified Mercalli Intensity with increasing distance. These may be used to develop empirical relationships for the decrease in peak ground acceleration with increasing distance from the earthquake epicenter.

The analysis of instrumentally recorded data can yield important information concerning the dependence of attenuation on frequency. Such data are needed for frequency-dependent scaling of response spectra and, in particular, for estimating ground motion spectra for sites near the epicenter based on spectra obtained at distant seismographs.¹⁶

Acceleration attenuation curves were developed by Schnabel and Seed (1973) for use in the western United States (from the Rocky Mountains westward) and are assumed to be bedrock accelerations.¹⁷ These curves are still used for many applications. Algermissen and Perkins (1976) modified the Schnabel and Seed curves for attenuation in the central and eastern part of the country.¹⁸ The modified acceleration attenuation curves are shown in Fig. K.1.

Attenuation curves for velocity¹⁹ were developed by Perkins, Harding, and Hanson, using the same general techniques and a portion of the ensemble of strong-motion records used by Schnabel and Seed in their study. Figure K.2 shows velocity attenuation curves developed for the western United States (west of the Rockies) and for the central and eastern United States. These attenuation curves were used in the development of the national probabilistic acceleration and velocity maps.¹⁹

Because of the lack of data or recordings of strong ground motion, differences in attenuation curves for areas of the eastern United States may be large; thus, it is of interest to examine some of these differences. Figures K.3 and K.4 show selected acceleration and velocity

Fig. K.1. Acceleration attenuation curves. Solid lines are curves used for eastern region. Dashed lines together with solid lines at close distances are attenuation curves used for western region.

attenuation curves developed by Nuttli and Herrmann (1981) for the mid-west and eastern United States.²⁰

Attenuation of intensities in the eastern United States is an important source of acceleration and velocity for a specific site. Just as the previously discussed attenuation curves can be used to give a value of ground motion (acceleration or velocity) at a site some distance from

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Fig. K.2. Velocity attenuation curves. Solid lines are curves used for eastern region. Dashed lines together with solid lines (in some instances) at close distances are attenuation curves used for western region.

Fig. K.3. Comparison of Algermissen and Perkins (1976) and Nuttli and Herrmann (1981) acceleration attenuation curves for eastern and central United States.

Fig. K.4. Comparison of Perkins (1980) and Nuttli and Herrmann (1981) velocity attenuation curves for central and eastern United States.

the epicenter, the attenuation intensity relations can be used to give the intensity at a site. The form of the attenuation relation accepted by most researchers is

$$I_s = I_0 + a + bR + c \ln R. \quad (K.1)$$

Table K.1 lists some of the more accepted relations for the eastern United States. The constants a , b , and c were developed by the different researchers by statistical analysis of their data and regression analysis of their data to fit the form of the relation. The exact procedures used are given in Refs. 21-27. The site intensity I_s and the epicentral intensity are given in Modified Mercalli Intensity units. The distance from the epicenter R is given in kilometers. Again, Table K.1, which lists the constants for each relation, points out the differences between each region of the eastern United States.

Table K.1. Attenuation of intensity in eastern United States

$$[I_s = I_0 + a + bR + c \ln R]^a$$

Region	Developer	Reference No.	a	b	c	Interval (km)
Charleston, South Carolina ^b	Bollinger	21	2.87	-0.00052	-1.25	$R > 10$
Giles County, Virginia	Bollinger	22	0.35	-0.0038	-0.34	
Central United States	Gupta-Muttli	23	3.7	-0.001	-1.17	$R > 20$
Modified Central United States ^b	LLNL	24	3.2	-0.0011	-1.17	$R > 15$
Southern Illinois	LLNL	24	0.35	-0.0046	-0.313	
Ossipee, New Hampshire	Weston Geophysical	25	7.441	-0.004	-0.67	
Eastern United States	Howell and Schultz	26	3.278	-0.0029	-0.989	
Eastern United States	Anderson	27	3.2	-0.00106	-1.17	

^a I_s = site intensity MMI;
 I_0 = epicentral intensity MMI;
 R = epicentral distance.

^b $R < \text{interval}$, $I_s = I_0$.

References

1. M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid, I. Low Frequency Range," *J. Acoust. Soc. Am.* 18, 168-78 (1956).
2. M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid, II. High Frequency Range," *J. Acoust. Soc. Am.* 28, 179-91 (1956).

3. M. A. Biot, "Mechanics of Deformation and Acoustic Propagation in Porous Media," *J. Appl. Phys.* 33, 1482-98 (1962).
4. M. A. Biot, "Generalized Theory of Acoustic Propagation in Porous Dissipative Media," *J. Acoust. Soc. Am.* 34, 1254-64 (1962).
5. J. B. Walsh, "Seismic Wave Attenuation in Rock Due to Friction," *J. Geophys. Res.* 71, 2591-99 (1966).
6. R. D. Stoll and G. M. Bryan, "Wave Attenuation in Saturated Sediments," *J. Acoust. Soc. Am.* 47, 1440-47 (1970).
7. J. E. White, "Computed Seismic Speeds and Attenuation in Rocks with Partial Gas Saturation," *Geophysics* 40, 224-32 (1975).
8. R. J. O'Connell and B. Budiansky, "Viscoelastic Properties of Fluid Saturated Cracked Solids," *J. Geophys. Res.* 82, 5719-36 (1977).
9. G. M. Mavko and A. Nur, "Wave Attenuation in Partially Saturated Rocks," *Geophysics* 44, 161-78 (1979).
10. D. H. Johnson, M. N. Toksoz, and A. Timur, "Attenuation of Seismic Waves in Dry and Saturated Rock: II. Mechanisms," *Geophysics* 55, 691-711 (1979).
11. R. F. O'Doherty and N. A. Anstey, "Reflections on Amplitudes," *Geophys. Prosp.* 19, 430-58 (1971).
12. K. Aki, "Analysis of the Seismic Coda of Local Earthquakes as Scattered Waves," *J. Geophys. Res.* 80, 3322 (1975).
13. K. Aki and B. Chouet, "Origin of Coda Waves, Source Attenuation and Scattering Effects," *J. Geophys. Res.* 80, 3322 (1975).
14. L. S. Gao et al., "Comparison of the Effects Between Single and Multiple Scattering on Coda Waves for Local Earthquakes," *Bull. Seismol. Soc. Am.* 73, 377-89 (1983).
15. Z. Der et al., "Spatial Coherence Structure and Attenuation of the Lg Phase, Site Effects, and Interpretation of the Lg Coda," *Bull. Seismol. Soc. Am.* 74, 1125-48 (1984).
16. O. W. Nuttli, R. Rodriguez, and R. B. Herrmann, *Strong Ground Motion Studies for South Carolina Earthquakes*, NUREG/CR-3755, Lawrence Livermore National Laboratory, April 1984.
17. P. Schnabel and H. B. Seed, "Acceleration in Rocks for Earthquakes in the Western United States," *Bull. Seismol. Soc. Am.* 63, 501-16 (1973).

18. S. T. Algermissen and D. M. Perkins, *A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States*, p. 45, U.S. Geological Survey Open-File Report 76-416, 1976.
19. S. T. Algermissen et al., *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States*, U.S. Geological Survey Open-File Report 82-1033, 1982.
20. O. W. Nuttli and R. B. Herrmann, "Excitation and Attenuation of Strong Ground Motion" (Abstract), 21st General Assembly, IASPEI-AISPIT, London, Canada, July 21-30, 1981.
21. G. A. Bollinger, "Reinterpretation of the Intensity Data for the Charleston, South Carolina Earthquake," U.S. Geological Survey Professional Paper 1028-B, 1976.
22. TERA Corporation, *Systematic Evaluation Program (SEP), Ground Motion Attenuation*, Berkeley, Calif., 1980.
23. I. N. Gupta and O. W. Nuttli, "Spatial Attenuation of Intensities for Central U.S. Earthquakes," *Bull. Seismol. Soc. Am.* 66, 743-52 (1976).
24. D. L. Bernreuter, D. H. Chung, and C. P. Mortgat, *Seismic Safety Margins Research Program, Phase I Final Report - Development of Seismic Input*, NUREG/CR-2015, Vol. 3, Lawrence Livermore National Laboratory, January 1983.
25. D. L. Bernreuter, *Seismic Hazard Analysis, Application of Methodology, Results, and Sensitivity Studies*, NUREG/CR-1582, Vol. 4, Lawrence Livermore National Laboratory, October 1981.
26. B. F. Howell, Jr., and T. R. Schultz, "Attenuation of Modified Mercalli Intensity with Distance From Epicenters," *Bull. Seismol. Soc. Am.* 65(3), 651-65 (June 1974).
27. J. C. Anderson, "On the Attenuation of Modified Mercalli Intensity with Distance in the United States," *Bull. Seismol. Soc. Am.* 68(4), 1147-79 (August 1978).

Appendix L

THEORETICAL COMPUTATION OF SEISMIC DESIGN SPECTRA

Theoretical calculations are important in the construction of the ground motion spectra needed for engineering design in the eastern United States. This need arises because insufficient observational data are available from major earthquakes in the region for predicting strong ground motion resulting from future earthquakes. Theoretical calculations can supplement the limited base of observational data available and provide a mechanism whereby knowledge gained from the study of moderate earthquakes in California can be included in the seismic design process elsewhere.

The eastern United States experiences few major earthquakes; therefore, it is unlikely that sufficient data will become available to construct empirical design spectra. The largest known earthquakes (the 1886 Charleston, South Carolina, and the 1811-12 New Madrid, Missouri, earthquakes) occurred prior to the development of modern recording seismographs. Further, design spectra constructed by empirical methods, using data from the western United States or other parts of the world, do not apply directly in the eastern United States because of differences in the seismic faulting and attenuation that exist between different regions. It is therefore necessary to translate the empirical results obtained in other regions to the eastern United States, based on theoretical considerations. In this translation, correct understanding of seismic wave generation and propagation in each region is essential.¹

Engineering design requires both an amplitude spectrum and a duration for the vibratory ground acceleration, especially at frequencies greater than about 1 Hz. Theoretical techniques may be employed to estimate either the amplitude spectrum or the complete ground motion time history for a hypothetical earthquake. The success of the mathematical model may be judged by comparison of the theoretical results with empirical data from regions where ample data exist for such a comparison. In general, it is more difficult to mathematically model the time history of the ground motion than its amplitude spectrum only. In addition, the

difficulty is greater at higher frequencies. It is also important to understand that the motion of a fault during an earthquake has a stochastic aspect in the sense that the details of the fault rupture cannot be predicted in advance of the earthquake. Although larger-scale parameters such as the average rupture velocity may be estimated, the details of the motion may vary. The effect of this stochastic variability is concentrated at higher frequencies and may alter the time history of the acceleration somewhat without substantially affecting its amplitude spectrum or duration.

Stochastic models have been developed for the purpose of predicting peak horizontal ground acceleration, velocity, and the shape of the response spectrum.²⁻⁷ These models assume a particular mathematical form for the spectrum and include parameters that allow for variations in the focal mechanism, seismic moment, epicentral distance, and attenuation to produce theoretical spectra, which can be compared to empirical results.

A number of different deterministic techniques are used to mathematically simulate seismic ground motion. Each has advantages in the complexity of the earth structure that can be handled, completeness of the mathematical representation, or computation time required. A brief summary of the different methods will be presented here, but it is important to note that this is an area of great interest among seismologists and is the focus of many research initiatives. Advances in this area will also be influenced by the increasing availability of large computers.

The existing deterministic methods can be broadly classified into (1) those that are restricted to layered earth models and (2) those that permit laterally varying media. Aki¹ presents a concise history of the development of simulation techniques that use layered earth models. These techniques use relatively simple earth models, in the sense that these consist of layers whose properties change with depth, but not lateral position. In essence, they adopt the point of view that the propagation of seismic waves through the earth can be represented by combining the normal modes of structural vibration, taking into account the level of excitation of each mode by the earthquake. Methods within this broad classification differ in the way that the integration over the modes is

performed and in the numerical approximations that are made. Harkrider⁸ has reviewed some of the different approaches.

Techniques that can compute a synthetic seismogram for the case of a realistic earth, in which the physical properties change with lateral position as well as with depth, have been studied extensively. Conceptually, these methods involve following the trajectories of individual rays emitted by the seismic source through the earth model. At any boundary within the model where the physical properties change, there is the possibility that several new rays will be generated that represent the reflected and transmitted energy, as well as the conversion of compressional waves into shear or vice versa. All of these waves must be followed as they traverse the model and are themselves reflected and transmitted at the boundaries they encounter. The internal earth structure is generally represented by polygonal regions, within each of which the physical properties are constant. The ground motion at any particular location on the surface is determined by the superposition of all rays that terminate there. In practice, there are a number of methods within this category, including finite difference,⁹ finite element,¹⁰ ray methods,¹¹ and others. These methods are capable, in principle, of producing theoretical seismograms for complex earth models. In practice, the structure of the earth may not be known in sufficient detail to construct the requisite mathematical model. The availability of powerful computers also imposes practical limitations on the complexity of the earth structure and the completeness of the seismic wave field that can be simulated.

References

1. K. Aki, "Earthquake Source Mechanism," *Earthquake Source Modeling, Ground Motion, and Structural Response*, American Society of Mechanical Engineers, PVP-Vol 80, New York, 1984, pp. 1-12.
2. T. C. Hanks, "Seismological Aspects of Strong Motion Seismology," *Proc. 2nd U.S. Nat. Conf. Earthquake Eng.*, Earthquake Engineering Institute, Berkeley, Calif., 1979, pp. 898-912.

3. T. C. Hanks, "b Values and w-g Seismic Source Models: Implications for Tectonic Stress Variations Along Active Crustal Fault Zones and the Estimation of High-Frequency Strong Ground Motion," *J. Geophys. Res.* 84, 2235-42 (1979).
4. R. K. McGuire and T. C. Hanks, "RMS Accelerations and Spectral Amplitudes of Strong Ground Motion During the San Fernando, California, Earthquake," *Bull. Seismol. Soc. Am.* 71, 1907-19 (1981).
5. T. C. Hanks and R. K. McGuire, "The Character of High-Frequency Strong Ground Motion," *Bull. Seismol. Soc. Am.* 71, 2071-95 (1981).
6. D. M. Boore, "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra," *Bull. Seismol. Soc. Am.* 73, 1865-94 (1983).
7. W. B. Joyner, "A Scaling Law for the Spectra of Large Earthquakes," *Bull. Seismol. Soc. Am.* 74, 1167-88 (1984).
8. D. G. Harkrider, "Synthetics and Theoretical Seismology," *Rev. Geophys. Space Phys.* 6, 1299-1308 (1983).
9. D. M. Boore, "Finite Difference Methods for Seismic Wave Propagation in Heterogeneous Materials," in *Seismology: Surface Waves and Earth Oscillations* (Methods in Computational Physics. Vol. II), B. A. Bolt, ed., Academic Press, New York, 1972.
10. J. Lysmer and L. A. Drake, "A Finite Element Method for Seismology," in *Seismology: Surface Waves and Earth Oscillations* (Methods in Computational Physics, Vol. II), B. A. Bolt, ed., Academic Press, New York, 1972.
11. T. L. Hong and D. V. Helmberger, "Glorified Optics and Wave Propagation in Nonplanar Structure," *Bull. Seismol. Soc. Am.* 68, 1313-58 (1978).

Appendix M

GROUND MOTION MODELS

A technique proposed by Nuttli¹ attempts to overcome the problem associated with relying on correlations between ground motion and Modified Mercalli Intensity (MMI) to estimate peak accelerations in the eastern United States. The approach has been to estimate MMI from an intensity attenuation relationship appropriate for the region under study, then to estimate ground motion from MMI using correlations based on western United States data. Studies have shown such approaches to yield potentially unreliable estimates of ground motion. Nuttli used a theoretical attenuation relationship for the higher mode surface waves (L_g waves) to model the attenuation of strong ground motion in the United States. The equation has the form

$$GMP(R) = A(R)R^{-5/6} e^{-\gamma R}, \quad (M.1)$$

where $GMP(R)$ is the amplitude of the ground motion parameter (acceleration, velocity, or displacement) at an epicentral distance R , $A(R)$ is source amplitude, $R^{-5/6}$ is a factor that accounts for geometric spreading and scattering, and $e^{-\gamma R}$ accounts for anelastic attenuation, γ being the coefficient of anelastic attenuation or absorption. By identifying R as the epicentral distance, it is assumed that body waves travel a horizontal path through the upper crustal layers.

For purposes of discussing anelastic attenuation of short period earthquake waves that travel through the earth's crust, the United States can be divided into two regions separated by the Rocky Mountains. The western region is marked by strong attenuation of waves having 1-Hz frequency, and the eastern region by much less attenuation. Differences in the specific quality factor Q exist for these two regions. The specific quality factor is observed to be a function of wave frequency f and is related to the coefficient of anelastic attenuation γ by the equation

$$Q(f) = \pi f / \gamma V, \quad (M.2)$$

where V is the group velocity of the waves; therefore, γ is given by

$$\gamma = \pi f / Q(f) V . \quad (M.3)$$

Nuttli assumed that the quality factor could be written as

$$Q(f) = Q_0 f^s , \quad (M.4)$$

where Q_0 is the specific quality factor of waves of 1-Hz frequency (L_g waves). Contoured values of Q_0 have been obtained from the coda of the L_g waves for the United States. Then γ can be written as

$$\gamma = \pi f^{1-s} / V Q_0 . \quad (M.5)$$

Now, to write the ground motion Eq. (M.1) in a more usable form, $A(R)$ is written in the form

$$A(R) = 10^{b+cm_b} , \quad (M.6)$$

where b and c are constants and m_b is, of course, body wave magnitude of 1-Hz frequency. The variable $R^{-5/6}$ is assumed to be a function of the distance from the site to the earthquake hypocenter. This variable is recast in the form

$$D = (R^2 + h^2)^{1/2} , \quad (M.7)$$

where h is the focal depth and R is the epicentral distance, so that

$$R^{-5/6} = [(R^2 + h^2)^{1/2}]^{-5/6} . \quad (M.8)$$

In this way R is always considered to be the epicentral distance. Then Eq. (M.1) can be rewritten as

$$GMP(R) = 10^{b+cm_b} [(R^2 + h^2)^{1/2}]^{-5/6} e^{-\gamma R} . \quad (M.9)$$

Equation (M.9) can be written in logarithmic form as follows

$$\log GMP = b + cm_b - 5/6 \log (R^2 + h^2)^{1/2} - dR , \quad (M.10)$$

where d is equal to $\gamma \log e$.

Strong motion studies that are used for engineering purposes are concerned with ground motions that have frequencies in the range of 0.1 to 25 Hz. From catalogs of strong motion observations it can be observed that peak displacements generally have frequencies <1 Hz. Peak ground velocities generally have frequencies in the range of 0.5 to 3 Hz, and peak accelerations generally have frequencies of 5 Hz and higher.

The method used to develop the correct constants for Eq. (M.10) is a semitheoretical or semiempirical one. The absence of rupture led Nuttli et al.² to propose the following relation between minimum focal depth and body wave magnitude for vertical fault plane earthquakes in the eastern United States:

$$\log h \text{ (km)} = -1.730 + 0.456 m_b \text{ for } m_b > 4.4 ,$$

$$\log h \text{ (km)} = -0.949 + 0.284 m_b \text{ for } m_b < 4.4 . \quad (\text{M.11})$$

If the fault plane dips at an angle to the horizontal, the value of minimum h should be multiplied by the sine of the angle. In the eastern United States for a typical midplate region, theoretical and observational studies by Bernreuter et al.³ and Nuttli et al.² indicate that for an eastern earthquake, Eq. (M.10) will take the following form for displacement:

$$\log d = -3.43 + 0.75 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.00017 R \text{ for } m_b < 4.5 ,$$

$$\log d = -6.81 + 0.5 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.00017 R \text{ for } m_b > 4.5 . \quad (\text{M.12})$$

The 34th percentile is given by multiplying d by 2.45 representing a standard error of 0.39 on $\log d$; the form for velocity is

$$\log V = -1.35 + 0.5 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ 0.00033 R \text{ for } m_b < 4.5 ,$$

$$\log V = -3.60 + 1.0 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.00033 R \text{ for } m_b > 4.5 . \quad (M.13)$$

The 84th percentile is given by multiplying V by 1.91, representing a standard error of 0.28 on $\log V$.

For the central or eastern United States, the assumed form of Eq. (M.4) is

$$Q(f) = Q_0 f^S = 1000 f^{0.3} ; \quad (M.14)$$

using this value in Eq. (M.5) yields

$$\gamma = \pi f^{0.7} / V Q_0 . \quad (M.15)$$

Using these relations, the peak acceleration in the east takes on the form

$$\log a = 1.69 + 0.25 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.00039 f^{0.7} R \text{ for } m_b < 4.5 , \\ \log a = 0.57 + 0.5 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.00039 f^{0.7} R \text{ for } m_b > 4.5 . \quad (M.16)$$

The 84th percentile is given by multiplying a by 1.76. In Eqs. (M.12), (M.13), and (M.16), the peak displacements are in centimeters, the peak velocities are in centimeters per second, and the peak accelerations are in centimeters per square second. These values are the arithmetic average of the two horizontal components of ground motion. In particular for South Carolina, Nuttli, Rodriguez, and Herrmann² assumed the following relation for Eq. (M.4)

$$Q(f) = Q_0 f^{0.4} = 400 f^{0.4} , \quad (M.17)$$

which led to the peak acceleration relation as follows:

$$\log a = 1.69 + 0.25 m_b - 0.83 \log(R^2 + h^2)^{1/2} \\ - 0.000975 f^{0.6} R \text{ for } m_b < 4.5 ,$$

$$\log a = 0.57 + 0.5 m_b - 0.83 \log(R^2 + h^2)^{1/2} - 0.000975 f^{0.6} R \text{ for } m_b > 4.5 . \quad (M.18)$$

The 84th percentile is given by multiplying a by 1.76. This ground motion model varies as does the frequency, which should help in the development of the response spectra. Nuttli¹ calculated values of the coefficient of attenuation or absorption for the central or eastern United States. Based on his theoretical model and observational data, these coefficients can be used to develop theoretical models by other workers. In fact, Campbell⁴ developed another ground motion model using Nuttli's study¹ to develop a relationship between the coefficient of attenuation and magnitude. Campbell's model is an empirical rather than theoretical attenuation relationship for peak ground acceleration, so as not to be constrained to a far-field approximation. Near-source data of magnitudes 5.0 and greater were used to establish the amplitude and geometrical attenuation of the peak acceleration. The relationship assumed for modeling the attenuation of peak acceleration with distance is expressed by the equation

$$PGA = ae^{bM} [R + C(M)]^{-d} e^{-\gamma R} , \quad (M.19)$$

where PGA is peak ground acceleration, R is distance, M is magnitude, and γ is the attenuation coefficient. This functional form was selected because when used with regression analyses, it is capable of modeling possible nonlinear magnitude and distance effects in the near field. The far-field properties of this relationship are characterized by the coefficient b , which controls magnitude scaling; the coefficient d , which controls the geometrical attenuation rate; and the coefficient γ , which controls the rate of attenuation due to absorption. $C(M)$ modulates the PGA attenuation at distances close to the fault where little geometrical attenuation is expected. Since fault rupture dimensions scale exponentially with magnitude, the following relationship was used to model $C(M)$:

$$C(M) = c_1 e^{C_2 M} . \quad (M.20)$$

Campbell's Eq. (M.19) differs from Nuttli's relationship¹ in two ways. The first is that the geometrical attenuation term d was not fixed but determined by regression analysis. The second was the addition of the $C(M)$ parameter. Both of these differences are required to accommodate the near-source effects of extended fault rupture, which is associated with large earthquakes.

Campbell developed a relationship between γ , the attenuation coefficient, and magnitude M , using the calculated values developed by Nuttli.¹ The relationship for central or eastern United States is

$$\gamma = 0.23 - 0.0048 M + 0.00028 M^2 \quad (M.21)$$

with a standard error of 0.00022 km^{-1} .

Using a nonlinear, multiple regression, least-squares analysis, the constants for Eqs. (M.19) and (M.20) were fitted for both fault distance (closest distance to fault rupture surface) and epicentral distance. The following expression for the median (50th-percentile) value of peak acceleration in terms of *fault distance* was developed:

$$\text{PGA} = 0.0142 e^{0.79M} (R + 0.0286 e^{0.778M})^{-0.862} e^{-\gamma R} . \quad (M.22)$$

The 84th percentile value of PGA is obtained by multiplying the median value by a factor of 1.51, representing a standard error of 0.409 on $\ln \text{PGA}$.

The relation for epicentral distance for the median (50th-percentile) value of peak acceleration is

$$\text{PGA} = 0.0823 e^{0.922M} (R + 27.2)^{-1.27} e^{-\gamma R} . \quad (M.23)$$

The 84th-percentile value of PGA is obtained by multiplying the median by 1.73, representing a standard error of 0.548 on $\ln \text{PGA}$. The magnitude M in these equations is defined as

$$M = 1.64 m_b - 3.16 \quad (m_b > 5.59) ,$$

$$M = 1.02 m_b + 0.3 \quad (m_b < 5.59) . \quad (M.24)$$

Rodriguez² developed strong ground motion estimates in a very straightforward procedure for certain regions in the eastern United States. He developed a relationship between I_0 (intensity near the source) and magnitude m_b established for the available data. Isoseismal maps were used to obtain empirical attenuation curves for MMI intensities vs distance, and from these an empirical expression was derived for the MMI intensity vs magnitude and distance by applying a linear regression analysis. Using appropriate relations, the intensity values were then transformed and used in estimating horizontal ground accelerations, velocities, and displacements. The general form of his equation is

$$\log (\text{GMP}) = a + b m_b + c \log(R + h)^{1/2} + dR, \quad (\text{M.25})$$

where GMP is the ground motion parameter, R is the epicentral distance, h is focal depth, and m_b is magnitude. The procedure was applied to data for South Carolina; New Brunswick, Maine; and Sharpsburg, Kentucky. The relations for the eastern United States are given in Table M.1.

Table M.1. Strong ground motion estimates
for eastern United States

$$[\log (\text{GMP}) = a + b M_b + c \log (R + h)^{1/2} + dR]$$

Region	GMP	a	b	c	d
South Carolina	Acceleration	0.72	0.49	-1.0	-0.000119
	Velocity	-3.43	0.98	-1.0	-0.000119
	Displacement	-6.64	1.47	-1.0	-0.000119
New Brunswick, Maine	Acceleration	0.96	0.51	-1.29	-0.00098
	Velocity	-3.19	1.02	-1.29	-0.00098
Sharpsburg, Kentucky	Acceleration	0.45	0.44	-0.68	-0.00072
	Velocity	-3.17	0.88	-0.68	-0.00072

Three ground motion models appropriate for the eastern United States have been presented. One is semitheoretical, and the other two are completely empirical. However, one of the empirical models has in common the use of γ , the attenuation coefficient. Nuttli-calculated values for

γ are given in Table M.2. Using these values or other derived values, the ground motion parameters from two models can be calculated. All the models can be used to calculate near- and far-field values.

Table M.2. Wave frequency and absorption coefficients of maximum motion as a function of body wave magnitude for eastern United States earthquakes

m_b	Wave frequency ^a (Hz)	Absorption coefficients ^b (km^{-1})
<u>Acceleration</u>		
4.0	12	0.007
4.5	10	0.006
5.0	7	0.0045
5.5	(6)	0.004
6.0	(5)	0.003
6.5	(4)	0.0025
7.0	(3)	0.0018
<u>Velocity</u>		
4.0	7	0.004
4.5	5	0.003
5.0	4	0.0025
5.5	(3)	0.002
6.0	(2-3)	0.0015
6.5	(2)	0.0012
7.0	(1-2)	0.0009

^aParentheses indicate that values are estimated rather than based on observations.

^bThe values of the absorption coefficient are taken from Ref. 1.

References

1. O. W. Nuttli, "The Relation of Sustained Maximum Ground Acceleration and Velocity to Earthquake Intensity and Magnitude," in *State-of-the-Art for Assessing Earthquake Hazards in the United States*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Misc. Paper S-73-1, Report 16 (1980).
2. O. W. Nuttli, R. Rodriguez, and R. B. Herrmann, *Strong Ground Motion Studies for South Carolina Earthquakes*, NUREG/CR-3755, St. Louis University, April 1984.
3. D. L. Bernreuter et al., *Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results for Ten Sites*, NUREG/CR-3756, Lawrence Livermore National Laboratory, April 1984.
4. K. W. Campbell, "A Ground Motion Model for the Central United States Based on Near-Source Acceleration Data," *Proceedings of Earthquakes and Earthquake Engineering: The Eastern United States*, Vol. 1, pp. 213-32, Knoxville, Tenn., September 1981.

Appendix N

SYNTHETIC RESPONSE SPECTRA

The synthetic response spectra procedure discussed here is based on a study by Joyner.¹ The scaling law proposed by Joyner is based on the ω -squared model of Haskell² and Aki.³ The shape of the seismic spectrum and how it scales with earthquake size has been a topic of considerable interest to seismologists and engineers for the prediction of strong ground motion for engineering purposes.

The spectral scaling law uses a simple stochastic kinematic model³ to predict ground motion. The law is very similar in form to Aki's model given as

$$A(\omega) = \frac{A(0)\omega^2}{1 + (\omega/\omega_c)^2}, \quad (N.1)$$

where $A(\omega)$ is the acceleration spectrum, ω_c is the corner radian frequency, and $A(0)$ is a complex function proportional to seismic moment. The exact form of $A(0)$ is not important to this discussion and will not be defined any further; however, readers seeking more in-depth information should see Ref. 3.

The corner frequency ($f_c = \omega_c/2\pi$) is given in terms of the seismic moment by

$$f_c = 4.9 \times 10^6 \beta (\Delta\sigma/M_0)^{1/3}, \quad (N.2)$$

where $\Delta\sigma$ the stress drop is in bars, f_c is in hertz, β the shear wave velocity is in kilometers per second, and M_0 is in dyne-centimeters. The scaling law proposed here assumes an ω -squared spectrum; for constant $\Delta\sigma$, the high-frequency acceleration spectral level is proportional to the square root of the rupture area for earthquakes. This may be assumed valid for earthquakes smaller than a critical moment M_{0c} corresponding to rupture of the entire width of the seismogenic zone (major surface rupture), but cannot be presumed valid for larger earthquakes. The proposed scaling law postulates that proportionality between high-frequency

acceleration spectral level and square root of rupture area generally holds and applies to earthquakes with moments greater than M_{0C} .

For all ω -squared models, the high-frequency spectral level of acceleration scales as $M_0 f_c^2$. For the purpose of extending the scaling law to earthquakes with a moment greater than M_{0C} , a spectrum is introduced with two corner frequencies as shown schematically in Fig. N.1. The low-frequency and the high-frequency behavior of this spectrum is the same as described by Eq. (N.1); below the low-frequency corner f_A , the spectrum is proportional to frequency squared and above the high-frequency corner f_B , the spectrum is flat. More specifically, the spectrum is proportional to $M_0 f^2$ below f_A , proportional to $M_0 f_A^\alpha f^{2-\alpha}$ between f_A and f_B , and proportional to $M_0 f_A^\alpha f_B^{2-\alpha}$ above f_B . If f_c is set equal to $(f_A^\alpha f_B^{2-\alpha})^{1/2}$ as illustrated in Fig. N.1, the spectrum is essentially the same as described by Eq. (N.1). The assumption that f_A scales as L^{-1} (L is rupture length) and f_B scales as W^{-1} (W is rupture width) is implicit in the assumptions and analyses by Haskell, Aki, and Savage.^{2,3} For earthquakes greater than M_{0C} , W and f_B are fixed, and L scales as $M_0^{1/2}$ and f_A as $M_0^{-1/2}$. The high-frequency level scales as $M_0 f_A^\alpha f_B^{2-\alpha}$; for moments greater than M_{0C} , f_B is fixed, so the high-frequency level scales as $M_0 f_A^\alpha$ or equivalently as $M_0^{1-\alpha/2}$. The high-frequency level is proportional to the

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Fig. N.1. Schematic diagram of acceleration spectrum for proposed scaling law.

square root of rupture area, and since the width W is fixed, the rupture area scales as L , which scales as $M_o^{1/2}$, and therefore the high-frequency spectrum scales as $M_o^{1/4}$. This provides the equation for determining α :

$$1/4 = 1 - \alpha/2 ,$$

$$\alpha = 1.5 . \quad (N.3)$$

For earthquakes with a moment less than M_{oc} , f_B is proportional to f_A . Denoting the proportionality constant by λ , $f_A = \lambda f_B$ below M_{oc} , and f_B is a constant above M_{oc} . Equations for f_A , f_B , and f_C are

$$\left. \begin{aligned} f_A &= 4.9 \times 10^6 \beta \lambda^{-1/4} \left(\frac{\Delta\sigma}{M_o} \right)^{1/3} \\ f_B &= 4.9 \times 10^6 \beta \lambda^{3/4} \left(\frac{\Delta\sigma}{M_o} \right)^{1/3} \\ f_C &= 4.9 \times 10^6 \beta \left(\frac{\Delta\sigma}{M_o} \right)^{1/3} \end{aligned} \right\} M_o < M_{oc} ,$$

$$\left. \begin{aligned} f_A &= 4.9 \times 10^6 \beta \lambda^{-1/4} \Delta\sigma^{1/3} M_{oc}^{1/6} M_o^{-1/2} \\ f_B &= 4.9 \times 10^6 \beta \lambda^{3/4} \left(\frac{\Delta\sigma}{M_o} \right)^{1/3} \\ f_C &= 4.9 \times 10^6 \beta \Delta\sigma^{1/3} M_{oc}^{1/24} M_o^{-3/8} \end{aligned} \right\} M_o > M_{oc} . \quad (N.4)$$

In Ref. 1, the proportionality constant λ was chosen so that

$$\lambda = 4 , \quad (N.5)$$

in order for the spectra calculated by Boore's model⁴ and Joyner's model¹ to be similar for earthquakes less than M_{oc} .

To scale the acceleration spectrum shown in Fig. N.1, a_o is assumed to be proportional to $M_o^\alpha f_A^\alpha f_B^{2-\alpha}$, and then Fig. N.2 can be drawn. Two examples are developed to show the scaling procedure. One example chosen was an eastern earthquake event with an m_b of 6.07. Appendix G was used

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Fig. N.2. Scaled diagram of acceleration spectrum.

to estimate the seismic M_0 of 2.512×10^{25} dyne-cm, stress drop $\Delta\sigma$ of 26 bars, for this event, and Appendix M was used to estimate the peak acceleration of 0.7 g. The second example for an eastern event with an m_b of 5.5 gave an estimated value of $M_0 = 1.585 \times 10^{24}$, $\Delta\sigma = 13$ bars, and a peak acceleration of 0.337 g. The synthetic acceleration spectra for these two examples are shown in Fig. N.3. The spectra are plotted on two different tripartite graphs, one for frequency and one for period, and are shown in Figs. N.4 and N.5. It should be pointed out, no damping has been assumed or considered in these plots.

To develop response spectra for different damping values, a numerical procedure, such as is used in the computer code SIMQKE (Ref. 5), can be used. Also, time history can be computed.

Fig. N.3. Synthetic acceleration spectrum for two examples:
 (1) $m_b = 5.5$, $M_o = 1.585 \times 10^{24}$, $\Delta\sigma = 13$ bars, and (2) $m_b = 6.07$,
 $M_o = 2.512 \times 10^{25}$, $\Delta\sigma = 26$ bars.

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Fig. N.4. Synthetic spectra plotted vs frequency.

Fig. N.5. Synthetic spectra plotted vs period.

References

1. W. B. Joyner, "A Scaling Law for the Spectra of Large Earthquakes," *Bull. Seismol. Soc. Am.* 74(4), 1167-88 (August 1984).
2. K. Kasahra, *Earthquake Mechanics*, Cambridge University Press, Cambridge, Mass., 1981, 128-33.
3. K. Aki and P. G. Richards, *Quantitative Seismology, Theory and Methods*, Vol. II, W. H. Freeman and Co., San Francisco, 1980, pp. 799-849.
4. D. M. Boore, "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models for the Radiated Spectra," *Bull. Seismol. Soc. Am.* 73(6), 1865-94 (December 1983).
5. D. Gasparine and E. H. Vammarcke, *Evaluation of Seismic Safety of Buildings - Report No. 2, Simulated Earthquake Motions Compatible with Prescribed Response Spectra*, MIT CE R75-4, Massachusetts Institute of Technology, January 1976.

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